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RHEOCASTING

PROCEEDINGS OF A WORKSHOP HELD AT THE ARMY MATERIALS AND MECHANICS RESEARCH CENTER

Metals and Ceramics Information Center
Battelle
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7. Abstract: Work which resulted in semi-solid casting (Rheocasting) began in July 1970. The actual casting program was started in 1973.

   This report contains presentations given at a Workshop on Rheocasting held at the Army Materials and Mechanics Research Center, Watertown, MA, on 3-4 February 1977. The purpose of the meeting was twofold: (1) to disseminate information on the state-of-progress in the continuing development of Rheocasting, and (2) to obtain comments from industry on its future development to assist Department of Defense planning. In support of the latter purpose, a questionnaire was sent to attendees after the meeting requesting specific information on interest and involvement in Rheocasting and related secondary processes. The results are included in this report.

8. This report discusses the present status of a new casting method and traces its history.

9. This report will be useful to materials engineers, ceramists and die casting engineers.

10. Industries using information in this report will include automotive, aircraft, foundries, and die casting industries.

11. *Associations or Societies who may have mailing lists:* American Ceramics Society, American Society for Metals, Society of Manufacturing Engineers, SAMPE, American Foundrymen Society.

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Work which resulted in semi-solid casting (Rheocasting) began in July 1970. The actual casting program was started in 1973. This report contains presentations given at a Workshop on Rheocasting held at the Army Materials and Mechanics Research Center, Watertown, MA, on 3-4 February 1977. The purpose of the meeting was twofold: (1) to disseminate information on the state-of-progress in the continuing development of Rheocasting, and (2) to obtain comments from industry on its future development to assist Department of Defense planning. In support of the latter purpose, a questionnaire was sent to attendees after the meeting requesting specific information on interest and involvement in Rheocasting and related secondary processes. The results are included in this report. (Continued)

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9 State of the art rept.

Editors

10 Robert D. French
Army Materials and Mechanics Research Center

Frank S. Hodi
Army Materials and Mechanics Research Center

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INTRODUCTION

This booklet contains a program and extended abstracts of presentations given at a Workshop on Rheocasting held at the Army Materials and Mechanics Research Center, Watertown, MA, on 3-4 February 1977. The purpose of the meeting was twofold: (1) to disseminate information on the state-of-progress in the continuing development of Rheocasting, and (2) to obtain comments from industry on its future development to assist Department of Defense planning. In support of the latter purpose, a questionnaire was sent to attendees after the meeting requesting specific information on interest and involvement in Rheocasting and related secondary processes. The results are included with these abstracts.

Much of the early development of Rheocasting has been supported by the Department of Defense, including the U.S. Army Research Office, the Army Materials and Mechanics Research Center, Frankford Arsenal and major support funding from the Defense Advanced Research Projects Agency. The first purpose of this meeting, disseminating information, is an effort toward implementing the results of the research and development program.

SESSION I

HISTORICAL PERSPECTIVE

Program Chairman

F. R. Larsen,
Army Materials and Mechanics Research Center

A HISTORY OF THE DEVELOPMENT OF RHEOCASTING

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The concepts of Rheocasting and Thixocasting were developed at M.I.T. in 1971 in a project under sponsorship of Army Research Office. Subsequent support from AMMRC and Frankford Arsenal aided in its development and a major program on "Machine Casting Ferrous Alloys", sponsored by DARPA brought the program to its present state of development. This paper briefly describes Rheocasting and its related processes, and summarizes their development.

Rheocasting and related processes at their current stage of development, are shown schematically in Figures 1 - 5. The simple Rheocasting process is sketched in Figure 1. The Rheocast metal is produced continuously at fractions solid ranging up to about 70%. The semi-solid slurry is fed directly to a casting machine such as a cold chamber die casting machine and formed into parts. A modification of the Rheocasting process that we have termed "Thixocasting" is shown in Figure 2. The metal is fully solidified after leaving the Continuous Rheocasting machine. It is then reheated until it is soft enough to be cast and is fed to a cold chamber die casting machine.

Non-metallic (or other) particles or immiscible liquids can be readily added to the semi-solid Rheocast slurry and this material then cast. This process we call "Compocasting" and is shown schematically in Figure 3. A number of laboratories in this country and abroad have demonstrated that Rheocast metal can be fed directly to a continuous casting machine to produce "Rheocast" continuous castings. This process is shown schematically in Figure 4. Finally, one need not use a die casting machine to form semi-solid parts but could, for example, use a closed die forging press. This process, shown schematically in Figure 5, is termed Thixoforging.

Work on Rheocasting (although not yet under the name) began in July, 1970 with initiation of an Army Research Office contract at MIT on the deformation behavior of solidifying metal alloys. The major aim of that program was ".... to determine the basic mechanism of deformation behavior of partially solidified metal alloys". The central achievement of that work was the discovery by a doctoral student, David Spencer, working with Professor Mehrabian and myself, who showed that when tin-lead alloys were vigorously agitated during solidification, the dendrites could be completely broken up, and the resulting semi-solid mixture caused to behave as a slurry with very low viscosities at fractions solids as high as 0.5. The original structure obtained by Spencer is shown in Figure 6. A typical plot from his work of viscosity versus fraction solid is shown in Figure 7.

It should be noted that the viscosity of these semi-solid alloys is dependent upon shear rate. Increasing the shear rate reduces the viscosity while reducing the shear rate causes the viscosity to increase sharply. This is shown in Figure 8 and is the basis of

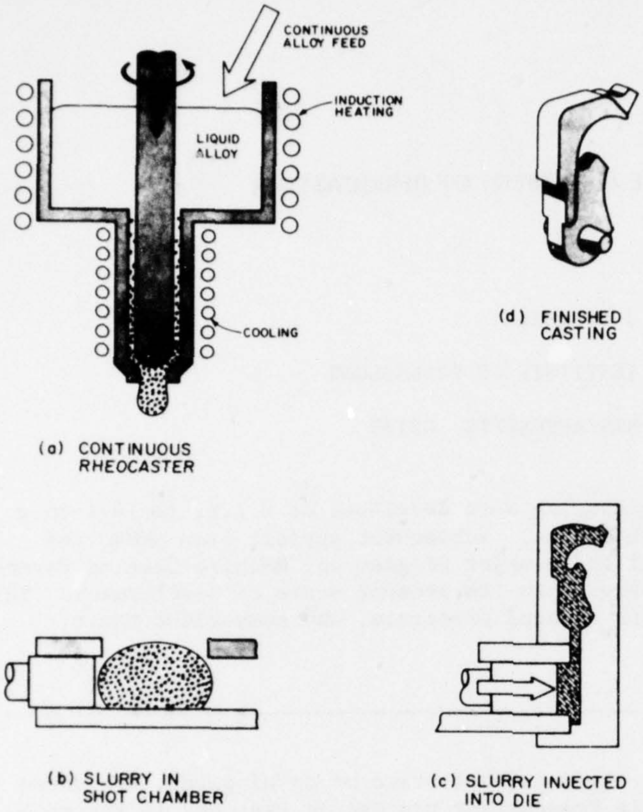

Figure 1: The Rheocast Process.

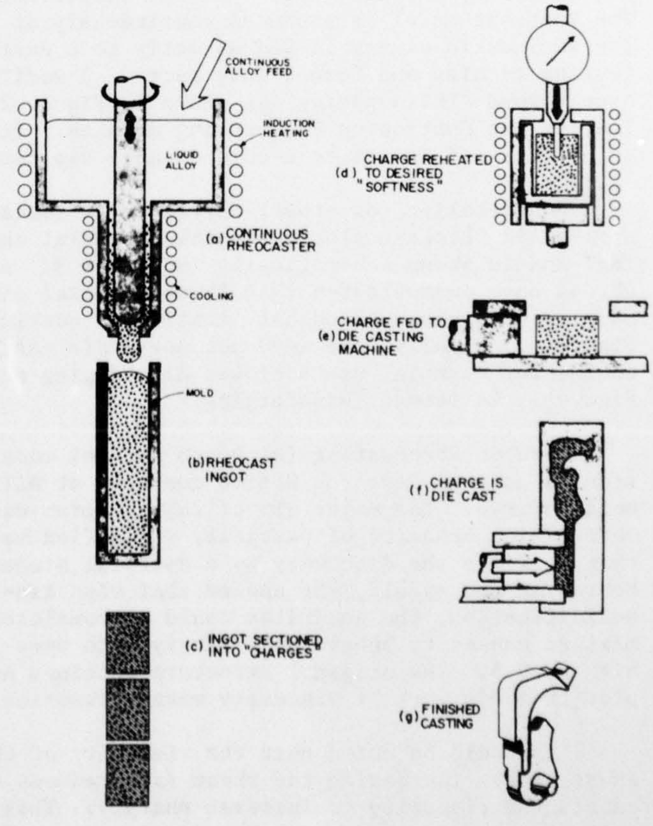

Figure 2: The Thixocasting Process.

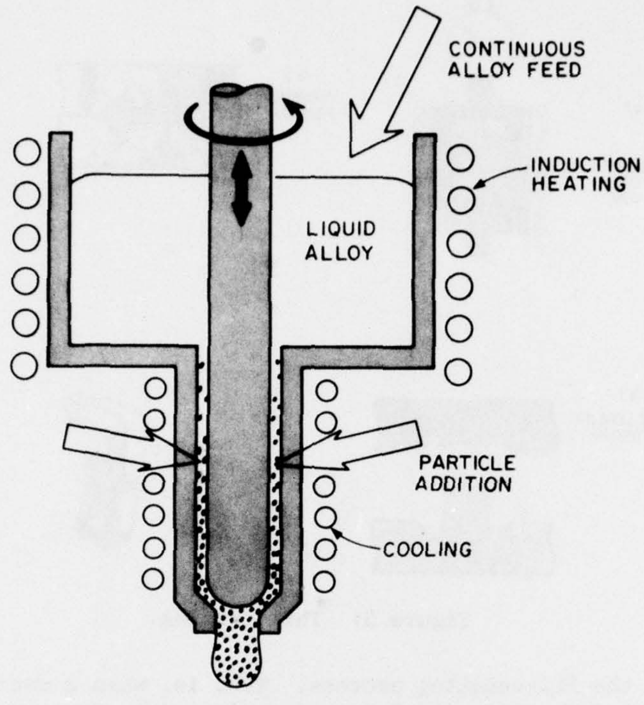

Figure 3: Continuous Compocasting.

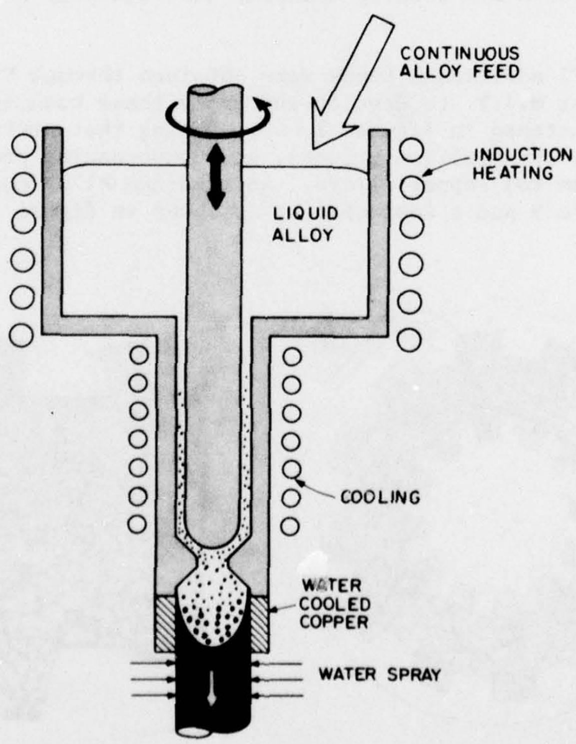

Figure 4: Continuous Casting via Rheocasting.

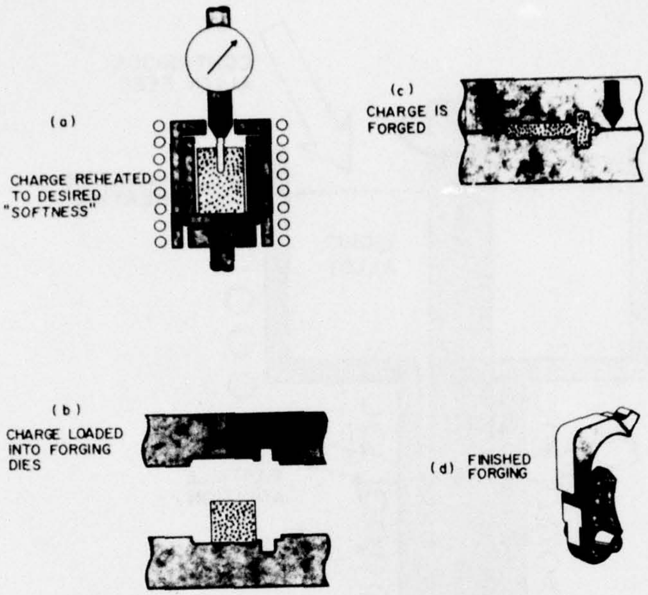

Figure 5: Thixoforging.

an important aspect of the Thixocasting process. That is, when a metal is held without stirring at, say, a fraction solid of 0.5 its viscosity rises to a very high value (perhaps as much as 10^7 poise, or about that of warm butter). At this high viscosity the metal can be handled much as a solid but when shearing begins, when the metal is forced through the narrow gate of a die casting machine, the viscosity drops rapidly and the metal flows smoothly.

During 1971 and 1972 additional funds were obtained through Frankford Arsenal and through AMMRC for work at M.I.T. to develop and apply these techniques to forming processes such as are sketched in Figures 1 - 5. During that period a rudimentary form of the Rheocasting process, Thixocasting process, and Compocasting process were developed and demonstrated for aluminum and copper alloys. An aluminum alloy casting made during that period is shown in Figure 9 and a Compocasting is shown in Figure 10.

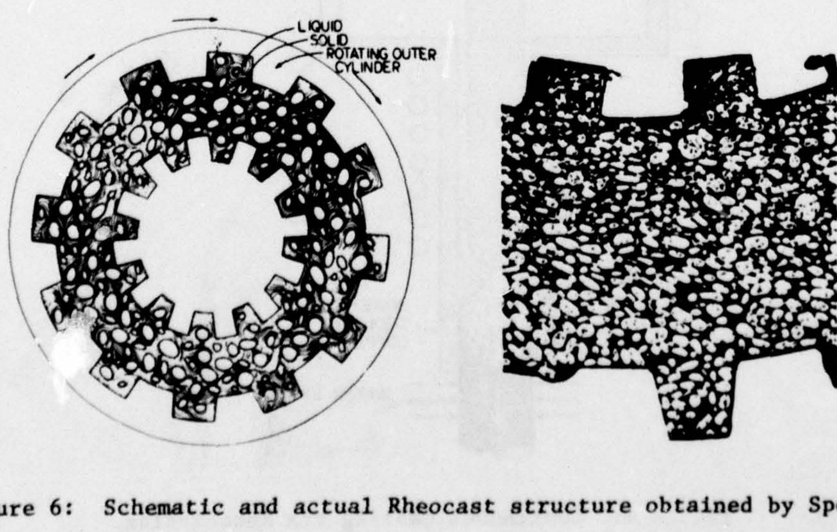

Figure 6: Schematic and actual Rheocast structure obtained by Spencer.

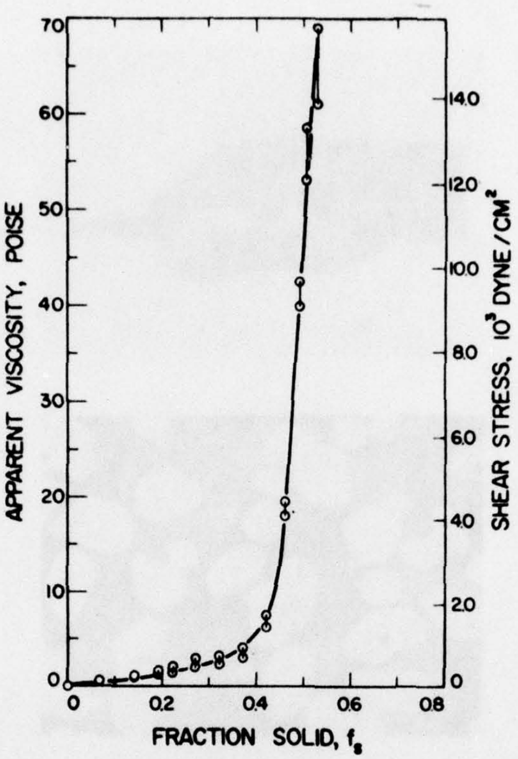

Figure 7: Typical apparent viscosity versus fraction solid curve for Sn-15wt% Pb alloy (at a given shear rate) (from Spencer).

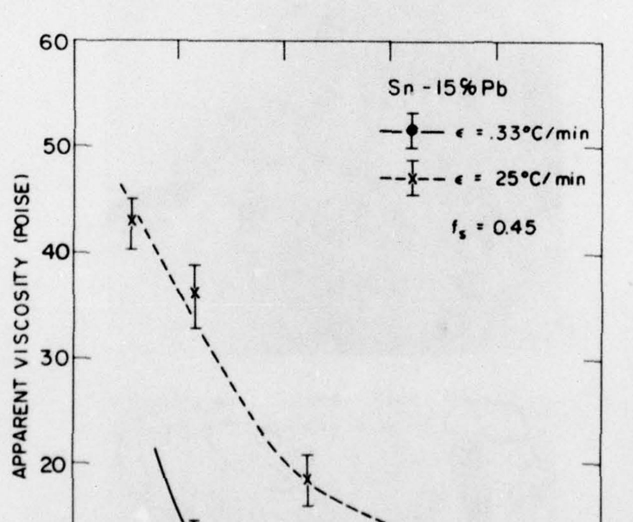

Figure 8: Variation of apparent viscosity with shear rate (from Joly).

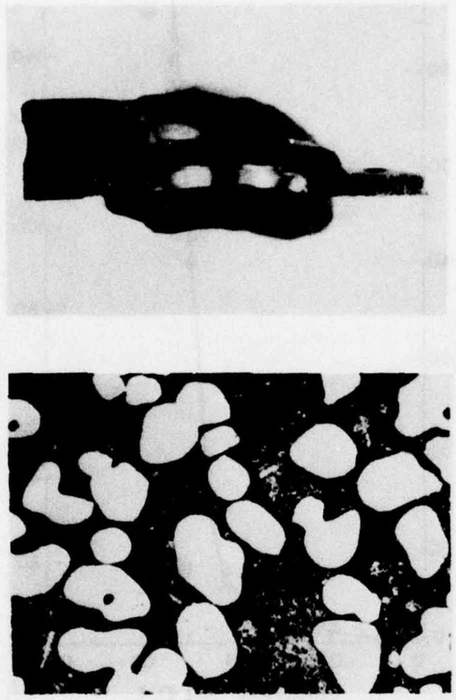

Figure 9: Aluminum alloy Rheocasting.

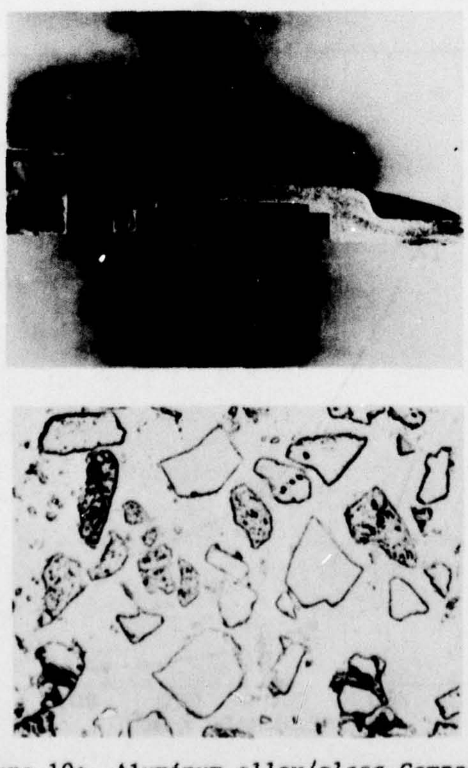

Figure 10: Aluminum alloy/glass Compocasting.

In January, 1973, DARPA, Defense Advanced Research Projects Agency initiated a program at M.I.T. on machine casting of ferrous alloys, the purpose of which was "to reduce substantially the cost of ferrous castings through major technical innovation of the casting process .... and to develop a system for making ferrous castings that would produce parts automatically at high speed and with high quality". Initial participants in this research program were Massachusetts Institute of Technology, Abex Corporation, Hitchiner Corporation, and General Electric Corporation. Participants later added were University of Illinois and Pratt and Whitney. Program objectives were the following:

Date	Program Objectives
January 1, 1973	Start.
July 1, 1974	Develop new technology and demonstrate the feasibility of its application to grey iron casting.
January 1, 1975	Demonstrate the feasibility of application of the new technology to steel casting.
January 1, 1976	Demonstrate the operability of a casting machine for cast iron, using the new technology.
January 1, 1977	Demonstrate the operability of a casting machine for steel, using the new technology.

All of these program objectives were met on time, a number of them significantly ahead of schedule. The only major difference in the progress of the program as compared with the program objectives outlined above is that in our work, as we developed new procedures and techniques, we did the initial work on tin-lead alloys, and then scaled up to copper base alloys. It was our original plan then to go on to cast iron, but each time we felt by the time we had mastered copper alloys we could go direct to steel.

The bulk of the work on casting of semi-solid alloys in this program has been carried out at M.I.T. Subsequent papers describe that work in detail. The high temperature Rheocasting process was developed and refined over a period of several years with important modifications being necessary as we moved to higher temperature metals. Rheocasting of steel required significantly improved refractories, careful control of heat input and output, and a reducing gas shield to minimize oxidation. A number of other significant innovations were introduced during the development program, including measurement of power (amperage) required to turn the rotor in the Continuous Rheocaster and the use of this measure to control fraction solid being produced by the Rheocaster.

The "softness tester" or "Penetrometer" shown in Figure 2 was developed in the course of the work to eliminate the need for thermocouples on reheating. Other innovations in the casting process have included automation of the "Thixoheater", development of casting procedures to fill the dies relatively slowly but eject them extremely rapidly (under about 0.2 seconds), and use of room temperature copper, water cooled dies. All of this work is discussed in more detail in the papers to follow.

A large number of papers, patents, and other publications have emanated from this program. The totals are listed below and a bibliography included in this booklet:

Patents granted	6
Patents pending	4
Theses in progress	8
Theses completed	10
Papers published	21
Articles published	4
Reports written	5

In addition to tangible results of this research program such as those listed above, many academic and industrial research laboratories in the U.S. and abroad have undertaken research activities on Rheocasting and related processes. Several companies have in the near future to find a market for products produced by these processes. Representatives of a number of the companies and laboratories are in attendance at this meeting and we will be hearing of some of their activities during the forthcoming sessions.

ACKNOWLEDGEMENTS

Research on this program at Massachusetts Institute of Technology has been conducted by 15 graduate students, 6 undergraduate students, and 6 research staff members.

Major contributions have been made by Dr. David B. Spencer in his doctoral thesis work and by Prof. R. Mehrabian, Dr. K. P. Young and Mr. R. G. Riek in supervising various portions of the activities. Most of the graduate students and others who have contributed significantly appear as co-authors of various publications listed in the bibliography enclosed herein.

SESSION II

RHEOCASTING

Session Chairman

P. A. Parrish
Army Research Office

FUNDAMENTAL ASPECTS OF RHEOCASTING

by

S.D.E. Ramati, D.G. Backman, Y.V. Murty, G.J. Abbaschian and R. Mehrabian

University of Illinois, Urbana-Champaign, Illinois

ABSTRACT

A brief review is given of the effect of process variables during Rheocasting on the structure and rheological behavior of the partially solidified slurries. Rheocast slurries are thixotropic and show a hysteresis loop phenomenon similar to other well known thixotropic systems. Results from fundamental studies on a high temperature viscometer are verified by extensive experiments carried out on Sn-15%Pb alloy and X-40 cobalt base superalloy in low and high temperature continuous Rheocast machines. The three important process variables affecting structure and viscosity of a Rheocast slurry are: average shear and cooling rates during primary solidification and volume fraction solid in the slurry. Increasing the average shear rate generally reduces the amount of entrapped liquid in the primary solid particles, resulting in a corresponding decrease in viscosity. Increasing the average cooling rate reduces the size of the primary solid particles, but increases the amount of entrapped liquid -- increases the effective volume fraction solid in the slurry, hence increases its viscosity. Primary solid particle size in Rheocast metals is approximately the same as primary dendrite arm spacing in a conventional casting solidified at equivalent cooling rate. As the volume fraction solid in a Rheocast slurry increases so do its primary solid particle size and its viscosity. Finally, a small laboratory apparatus is described that permits production of Rheocast ingots semi-continuously.

I. STUDIES CARRIED OUT ON A VISCOMETER

Fundamental work on vigorously agitated, partially solidified model system alloy Sn-15%Pb carried out in a high temperature viscometer has shown that the structure and rheological behavior of a metal slurry are a function of three process variables. These variables are: the average shear and cooling rates used during primary solidification and the volume fraction of solid in the slurry (1).

The general trends established relating process variables (average shear and cooling rates and volume fraction solid) to structure and viscosity of metal slurries are(1):

1. Increasing the average shear rate generally reduces the amount of entrapped liquid in the solid particles resulting in a corresponding decrease in viscosity. Shear rate also affects the size of the primary particles at very slow cooling rates $\sim 10^{-2}$°C/sec-- primary solid particle size decreases with increasing average shear rate.

2. Increasing the average cooling rate during primary solidification reduces the size of the primary solid particles, but increases the amount of entrapped liquid--increases the effective volume fraction of solid in the slurry, hence increases its viscosity, Figure 1.

3. As the volume fraction solid in a slurry increases, so does its viscosity, Figure 1.

4. For a given average shear and cooling rate, the relative viscosity* of a partially solid metal slurry, η_r, at volume fractions solid larger than ~ 0.2, can be described by an exponential equation, Figure 2.

$$\eta_r = A \exp Bg_s \qquad (1)$$

where A and B are constants depending on average shear and cooling rates, and g_s is volume fraction solid.

5. Metal slurries are thixotropic (their viscosity decreases with increasing rate of shear, is time dependent and reversible) and show a hysteresis loop phenomenon similar to other well known thixotropic systems, Figure 3. Measured areas of hysteresis loops (a quantitative measure of thixotropy) increase with increasing volume fraction solid, initial viscosity and time at rest, Figure 4.

6. Relative viscosities of partially solidified metal slurries are; (a) 1 to 2 orders of magnitude higher than suspensions of non-interacting spheres of polystyrene, rubber latex, glass and methylmethacrylate, and (b) of the same order of magnitude as suspensions of interacting particles like Kaolin (clay) in water. The high viscosity of the latter suspension has been explained on the basis of an aggregation mechanism (2). A similar mechanism has been proposed for the interacting solid particles in a metal slurry (1). Figure 5 shows data obtained for the slurries of an Sn-15%Pb alloy over a wide range of thermomechanical treatments, as well as reported data for the nonmetallic systems noted above.

Some of the observations listed above are summarized in Table I. Figure 6 shows two extreme types of structures obtained in slurries of Sn-15%Pb alloy under different processing conditions (1).

II. STUDIES CARRIED OUT ON CONTINUOUS RHEOCASTERS

Recent work at the University of Illinois on low and high temperature continuous Rheocasting apparatuses has shown that the process variables noted above affect the structure of continuously produced slurries in similar ways. Furthermore, primary solid particle size, p.p.s., in slurries of Sn-15%Pb alloy and X-40 cobalt base superalloy are of the same order of magnitude as primary dendrite arm spacings in conventional castings solidified under identical average cooling rates. Results of these studies are presented below. Finally, a method is described for production of semi-continuous ingots of Rheocast alloys with volume fractions solid as high as ~ 0.5.

Photographs and schematic illustrations of the high temperature slurry producer are shown in Figures 7 and 8. Detailed description of these apparatuses and their operating procedures are described elsewhere (3).

1. Process variables in a Continuous Rheocaster

The three important process variables in a continuous Rheocaster affecting structure are defined and methods available for their determination are described below.

---

*The relative viscosity of a suspension is defined as $\eta_r = \eta_a/\eta_o$ where η_a is apparent viscosity of the suspension and η_b is the viscosity of the liquid.

(a) Average shear rate. The average shear rate is a function of the rotor geometry, the clearance between the rotor and the lower mixing chamber, and the rotation speed. The following equation gives the average shear rate in the annulus in the mixing chamber.

$$\dot{\gamma}_{Ave} = \frac{2\Omega_0}{(1-\kappa^2)} \kappa \qquad (2)$$

where $\dot{\gamma}_{Ave}$ equals the average shear rate, Ω_0 is angular velocity and κ is defined as:

$$\kappa = \frac{\text{Perimeter of the rotor}}{\text{Perimeter of the mixing chamber}}$$

In the continuous Rheocasting machine of Figures 7 and 8, the value of κ is 0.86 and at a rotation speed of 1000 RPM the calculated average shear rate $\dot{\gamma}_{Ave} = 692 \text{ sec}^{-1}$.

(b) Average cooling rate. The average cooling rate is a function of the thermal profile within the mixing chamber including the temperature and volume fraction of solid of the discharged slurry. The average cooling rate in the mixing chamber is defined by the following equation:

$$\epsilon_{Ave} = \frac{\Delta T_s(g_s)}{t_f} \qquad (3)$$

where g_s is the volume fraction of primary solid particles in the slurry, $\Delta T_s(g_s)$ is the difference between the liquidus temperature and the temperature of the exiting slurry, and t_f is the residence time of the alloy in the mixing chamber while in the solidification range. The average cooling rate in the high temperature slurry producer is typically $\sim 1°C/sec$ during the production of X-40 cobalt base superalloy slurries.

(c) Volume fraction solid. The volume fraction solid of primary spheroidal solid particles in the exiting slurry is dependent on the rate of heat withdrawal in the mixing chamber, the rate of material flow through the chamber, and the physical properties of the metal produced. Once the temperature in the mixing chamber at the exit port has been determined (either through direct measurement or through analytical heat flow analysis) the volume fraction of solid can be determined using one of the following methods. For a binary alloy, in which the densities of the liquid and the solid are not too different, volume fraction solid and weight fraction solid are approximately equivalent, and the Scheil equation can be used.

$$g_s = 1 - \left(\frac{T_M - T_L}{T_M - T}\right)^{1/1-k} \qquad (4)$$

where g_s is the volume fraction solid, T_M is the melting point of the pure solvent, T_L is the liquidus temperature of the alloy and T is the actual temperature in the liquid-solid range.

For more complex alloy systems the relationship between volume fraction solid and temperature is established experimentally. First, a slurry of the alloy is produced at the highest volume fraction solid possible ($\sim$0.7 to 0.75) and slowly cooled in an ingot mold until solidification is complete. Now, reheating the alloy to different temperatures in the liquid-solid range followed by a rapid quench delineates the spheroidal solid particles existing at each temperature. Quantitative metallography is now carried out to establish the volume fraction solid of primary solid particles in each specimen and a master curve relating volume fraction solid to temperature in the liquid-solid range is established. This technique has successfully been used in a variety of alloy systems including bronze, steels, and nickel base superalloys (4,5).

2. Effect of Process Variables on Structure

The two alloys studied were the low temperature model alloy Sn-15%Pb and X-10 cobalt base superalloy. Initial results on continuously produced slurries confirm earlier findings (1) that average cooling rate during primary solidification has the most pronounced effect on the size of the primary solid particles.

Changes in average shear rate, at a given volume fraction solid and average cooling rate, did not significantly affect the size of the primary solid particles, Figure 9. Note that cooling rates were varied between 0.14 and 6.5°C/sec. This confirms earlier findings (1) that the effect of variations in rate of shear on the size of the solid particles in the slurry are only observed at relatively slow cooling rates of $\sim 10^{-2}$°C/sec -- primary solid particle size decreases with increasing average shear rate. However, increasing the shear rate does have an effect on the geometry of the particles. At a given cooling rate and volume fraction solid, increasing the shear rate reduces the amount of entrapped liquid in the solid particles. This observation is in line with previous findings (1) -- reduction in the amount of entrapped liquid results in a corresponding decrease in the effective volume fraction of solid in the slurry, hence its viscosity.

Previous experimental evidence (6) indicates that dendrite arm spacing in a given alloy cast from above its liquidus temperature is influenced only by the average cooling rate or local solidification time. Generally, segregate spacing is found to be inversely proportional to average cooling rate to an exponent (or directly proportional to local solidification time to the same exponent). The relationship for a given alloy is:

$$d = a t_f^{\,n} = b(\varepsilon_{Ave})^{-n} \qquad (5)$$

where d is dendrite arm spacing, a, b and exponent n are constants (different constants for primary and secondary dendrite arm spacing), t_f is local solidification time, and ε_{Ave} is average cooling rate defined in equation (3).

In the corollary experimental program, relationships between primary and secondary dendrite arm spacings were determined. Results of work on the effect of average cooling rate on primary particle size in continuously produced slurries were then compared with the segregate spacings in the dendritically solidified specimens, Figures 10 and 11. Primary solid particle size, p.p.s., in a slurry decreases with increasing cooling rate. This observation is not only in line with previous work on dendritically solidified castings, but our results indicate that the size of the particles in a slurry are approximately equivalent to the primary dendrite arm spacings in conventional castings solidified under identical average cooling rates.

The data in Figure 10 are for volume fractions solid in the range of 0.43 to 0.61. Drastic changes in volume fraction solid, for example from 0.2 to 0.6, do result in a corresponding increase in primary solid particle size; however, over the smaller range noted above the effect of cooling rate is much more pronounced. Finally, Figure 12 shows the microstructures of a dendritically solidified and continuously produced (water quenched) slurry of Sn-15%Pb alloy obtained at equivalent cooling rates.

The observations presented above are in line with our studies on the formation of primary solid particles in the transparent NH_4Cl-H_2O system. Solidification, during vigorous agitation, in this transparent system starts with formation of discrete primary dendrite stocks with a few secondary arms attached to each stock. As solidification proceeds, secondary arms remelt, break off, and coarsen. At the same time different particles have a tendency to weld and fuse together. Increasing the cooling rate at the beginning of solidification at equivalent shear rates, results in smaller dendrites and smaller spheroidal primary solid particles in the slurry.

3. Production of Semi-Continuous Rheocast Ingots

Commercial exploitation of this new technology requires production of Rheocast ingots at high speed in a continuous or semi-continuous operation. Studies at the University of Illinois have led to the development of a technique for production of semi-continuous Rheocast ingots. The feasibility of the process has been demonstrated on a laboratory apparatus on the Sn-15%Pb alloy.

A direct chill casting assembly was located below the low temperature continuous slurry producer as shown schematically in Figure 13. The mold is made of graphite with a slightly tapered cylindrical hole located in its center. The top half of the mold is heated with controlled resistance heating coils while the bottom half is water cooled. This arrangement coupled with vibration of the mold assembly permits production of smooth surface ingots with slurries containing volume fractions of primary solid as high as ~ 0.5. Finally, a water spray is directed on the ingot as it is withdrawn from the graphite mold by the pedestal and the withdrawal assembly. A photograph of an Sn-15%Pb ingot produced in this way is shown in Figure 14.

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REFERENCES

1. P. A. Joly and R. Mehrabian, "The Rheology of a Partially Solid Alloy," J. of Materials Science, 11, 1393-1418 (1976).

2. A. S. Michaels and J. C. Bolger, "The Plastic Flow Behavior of Flocculated Kaolin Suspensions," I and E. C. Fundamentals, 1, No. 3, 153-162 (1962).

3. R. Mehrabian, D. G. Backman, Y. V. Murty, G. J. Abbaschian, S. D. E. Ramati, S. Hong and R. J. Lauf, "Machine Casting of Ferrous Alloys," Semi-Annual Technical Report, ARPA Contract DAAG-46-76-C-0023, April 1, 1976 to September 30, 1976, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

4. R. G. Riek, A. Vrachnos, K. P. Young, N. Matsumoto and R. Mehrabian, "Machine Casting of a Partially Solidified High Copper Content Alloy," AFS Transactions, 19, 25-30 (1975).

5. J. M. Oblak and W. H. Rand, "Solid-Liquid Phase Characterization of Several Rheocast High Performance Alloys," Metallurgical Transactions B, Vol. 713, 699-703 (1976).

6. R. Mehrabian, "Segregation Control in Ingot Solidification," Solidification Technology, Burke, J. J. et al., Eds., Brook Hill Publishing Company, Chesnut Hill, Massachusetts, 299-315 (1974).

Table I

Relationship Between Viscosity and Structure of Sn-15%Pb Slurries (1)

(a) At a Given Volume Fraction Solid

Initial Shear Rate	Isothermally Held Specimens			Continuously Cooled Specimens					
				ε = 0.33°C/min			ε = 25°C/min		
$\dot{\gamma}_o$ ↑ Increases	η_a ↓ decreases	$\bar{X}$ ↓ decreases	g_{Le} ↔ No Change	η_a ↓ decreases	$\bar{X}$ ↓ decreases	g_{Le} ↓ decreases	η ↓ decreases	$\bar{X}$ ↔ No Change	g_{Le} ↓ decreases

(b) At a Given Volume Fraction Solid and Initial Shear Rate

Cooling rate ↑ε increases, ↑η_a increases ↓$\bar{X}$ decreases ↑g_{Le} increases

List of Symbols

$\dot{\gamma}_o$ = initial shear rate

η_a = apparent viscosity

$\bar{X}$ = average size of primary solid particle (minor axis)

g_{Le} = volume fraction of entrapped liquid

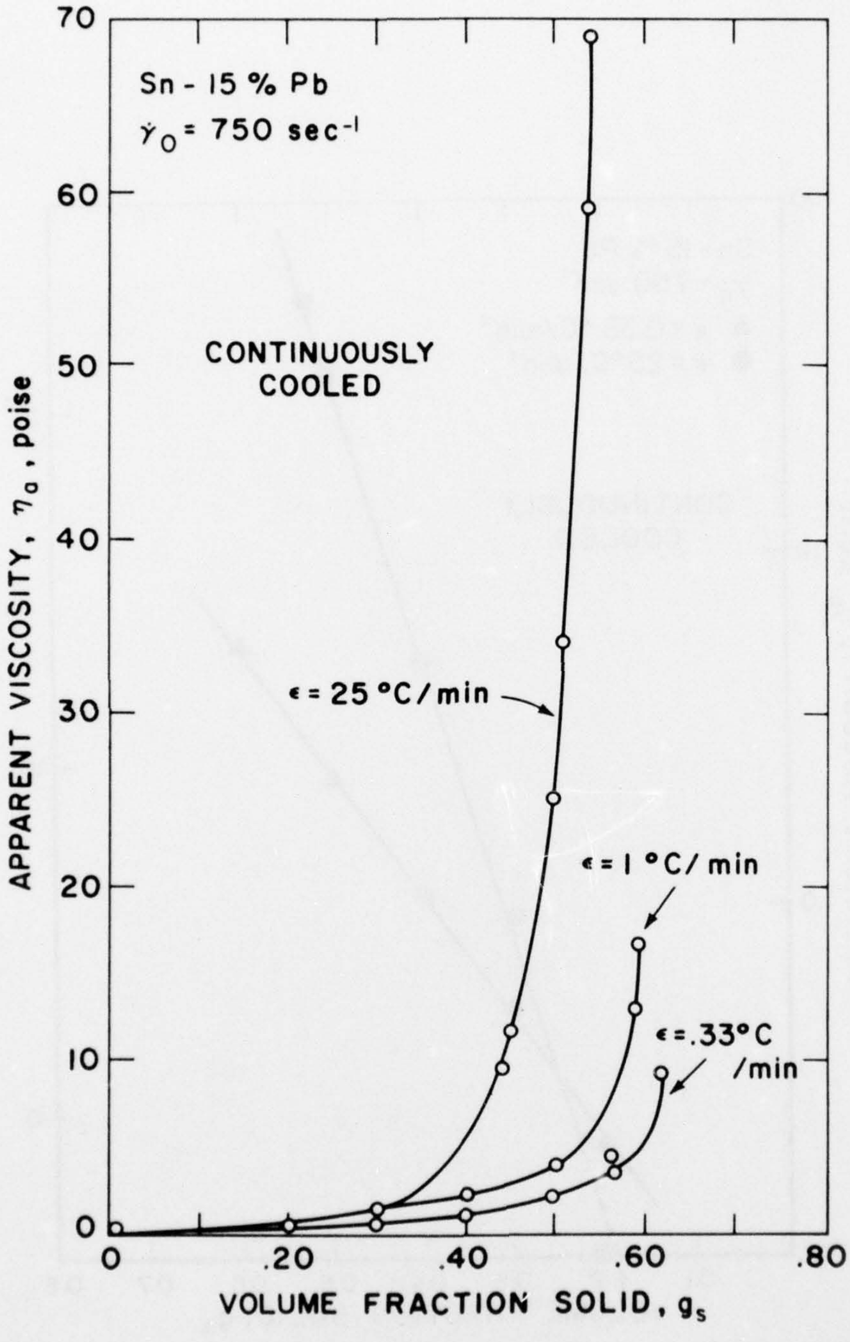


Figure 1. Apparent viscosity versus volume fraction solid of three samples sheared continuously at 750 sec^{-1} and cooled at constant rates of 0.33, 1.0 and 25°C/min(1).

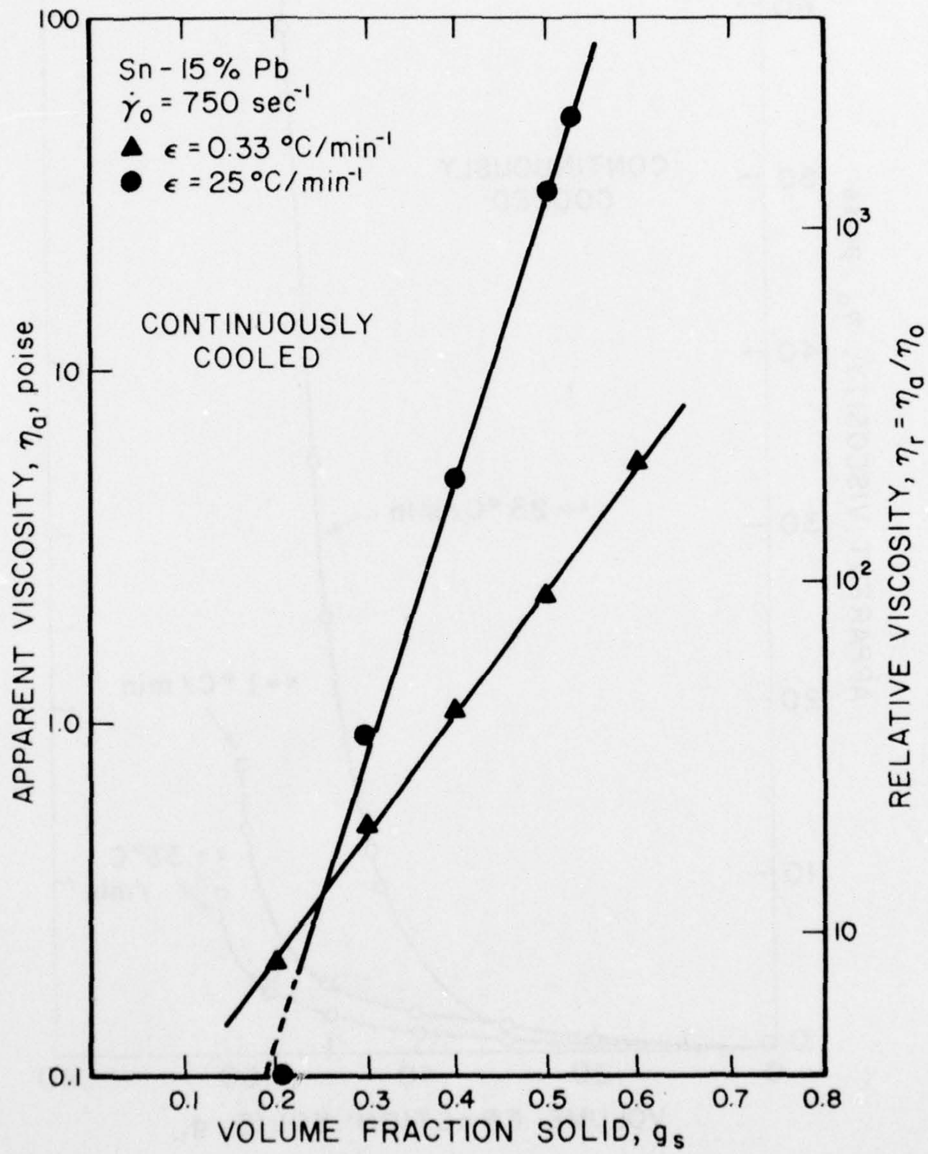


Figure 2. Apparent viscosity versus volume fraction solid of samples sheared continuously and cooled at a constant rate; semi-log plot (1).

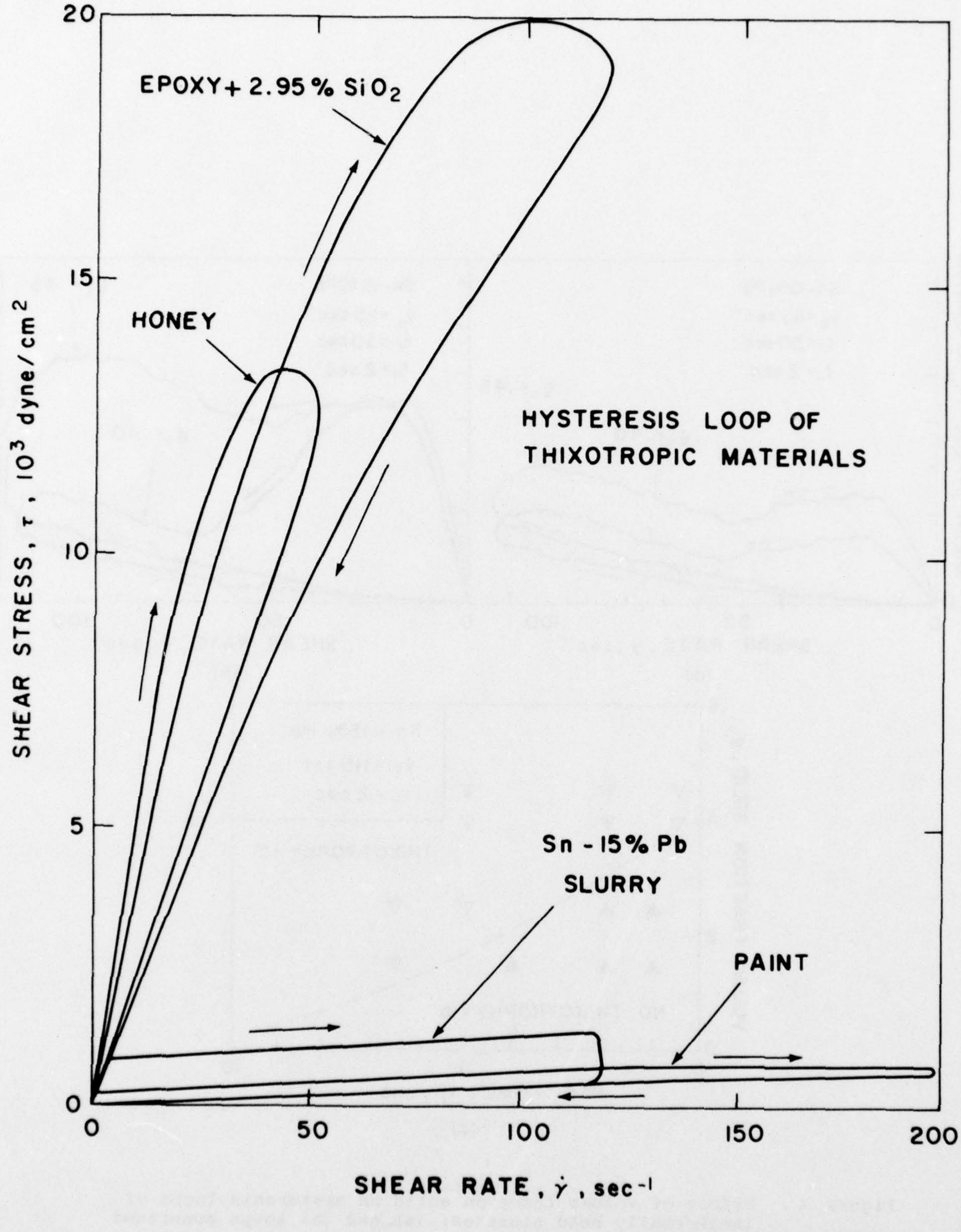


Figure 3. Hysteresis loops of non-metallic systems and a 0.45 volume fraction solid Sn-15%Pb alloy slurry(1).

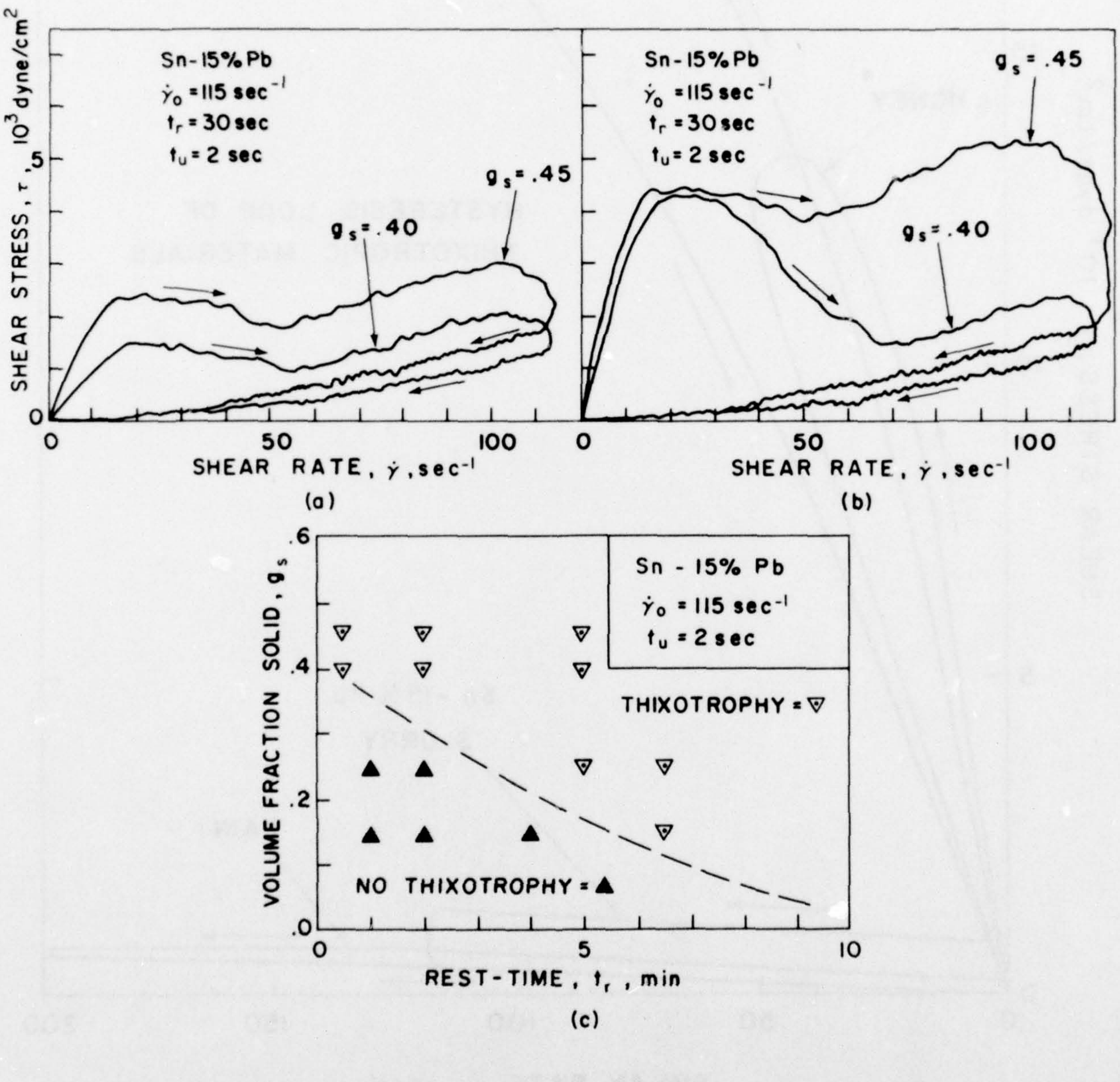


Figure 4. Effect of volume fraction solid on hysteresis loops of isothermally held slurries; (a) and (b) loops generated after rest-times of 30 and 120 seconds, respectively; (c) observation of measurable thixotropy as a function of volume fraction solid and time at rest(1).

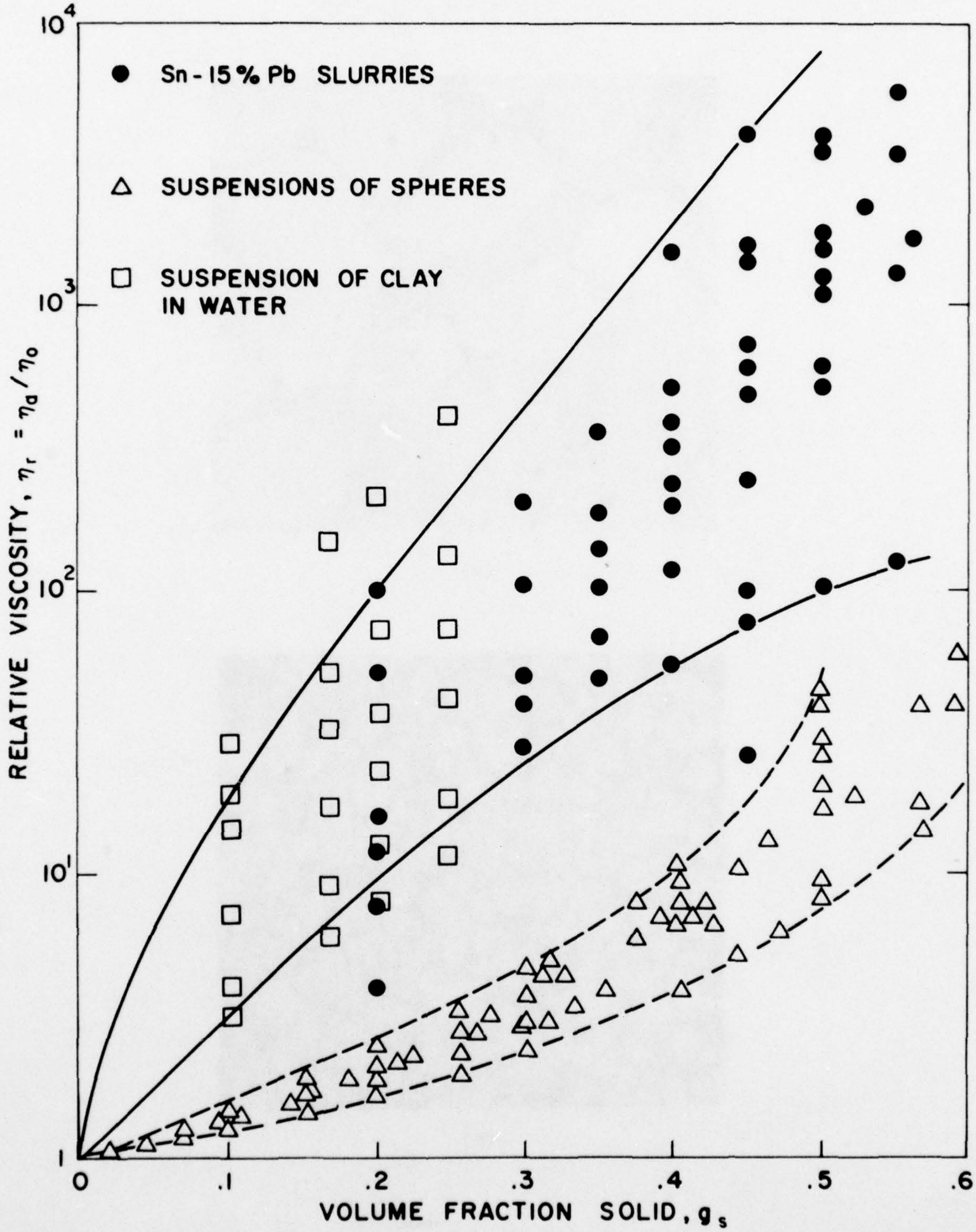
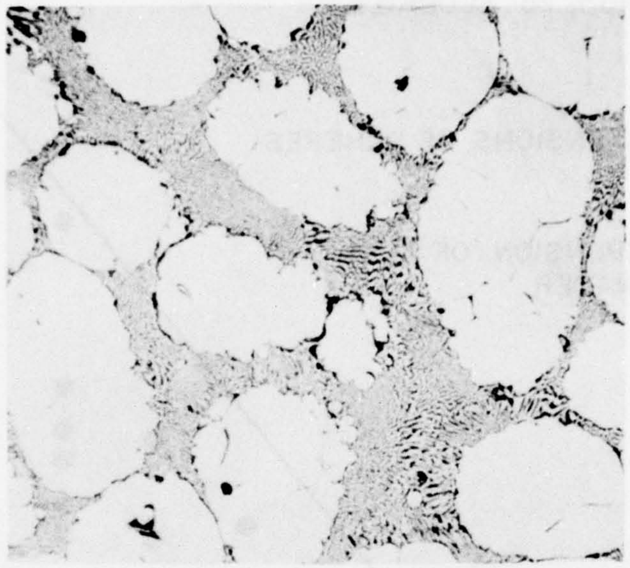
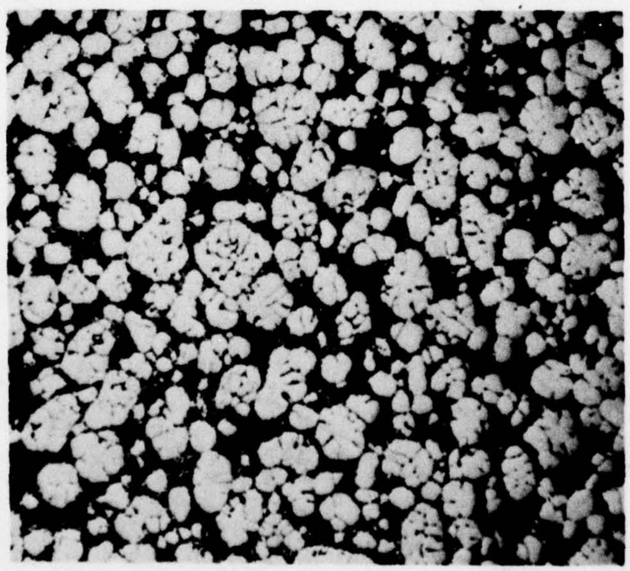


Figure 5. Comparison of the relative viscosity of Sn-15%Pb slurries to that of other suspensions of interacting and non-interacting particles (1).



(a)



(b)

Figure 6. Structure of Sn-15%Pb slurries processed under different conditions. (a) Average shear and cooling rates were 230 sec^{-1} and 0.33°C/min, respectively. (b) Average shear and cooling rates were 750 sec^{-1} and 25°C/min., respectively. Magnification 50X (1).

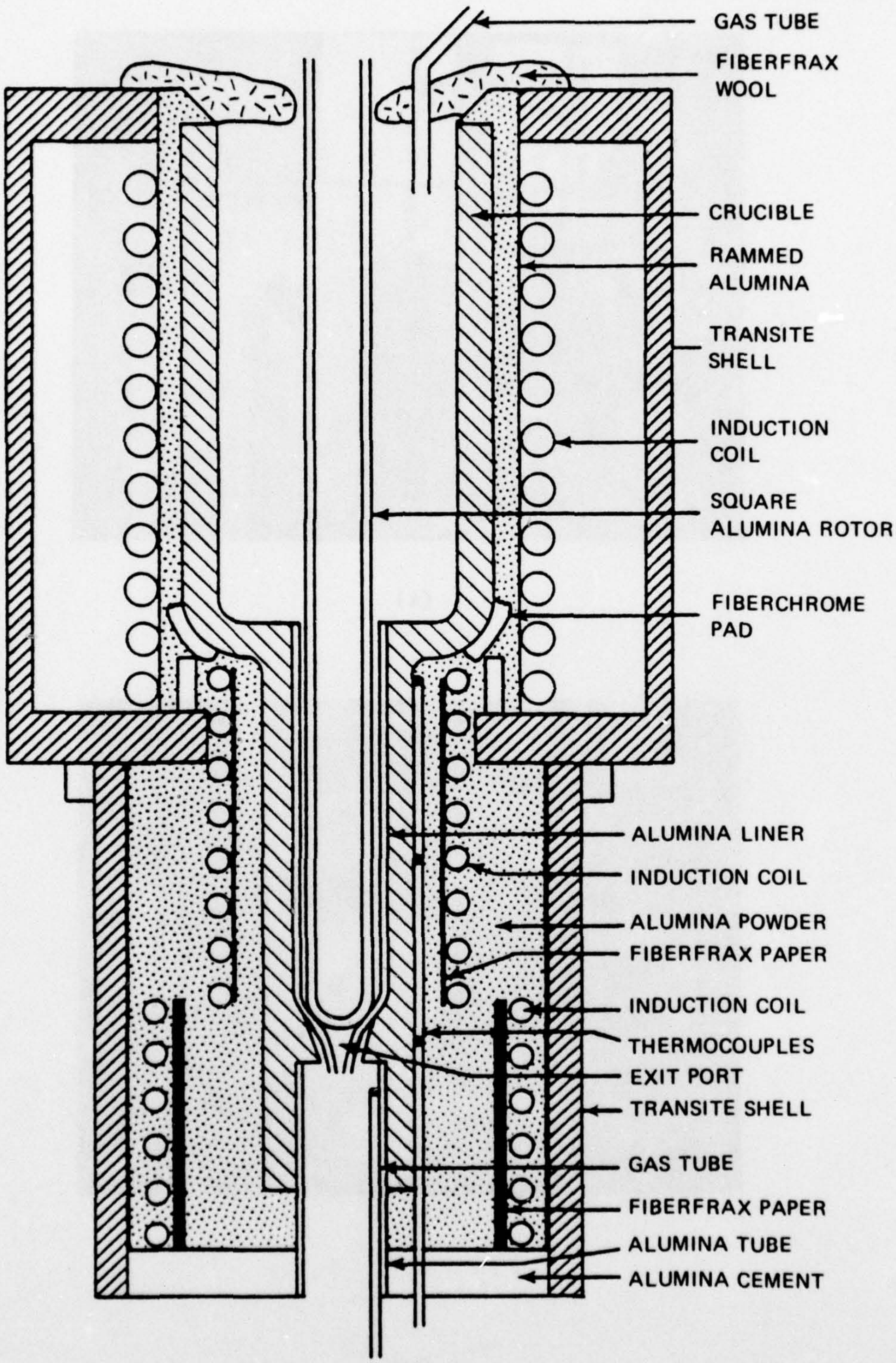
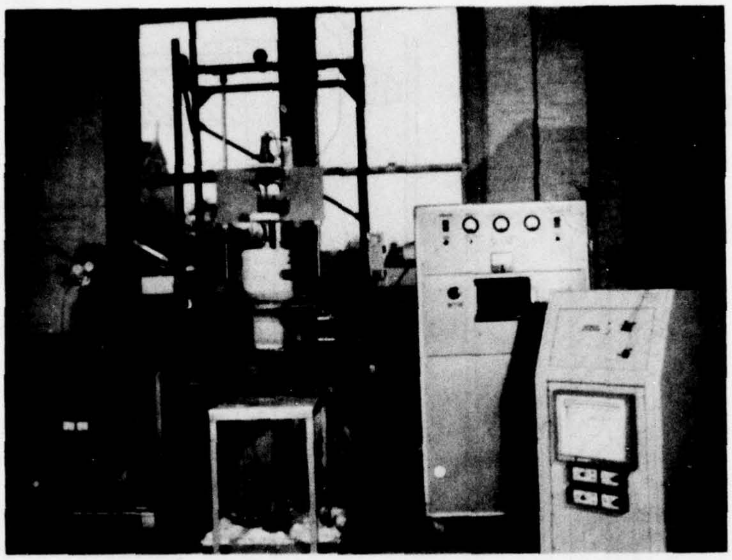
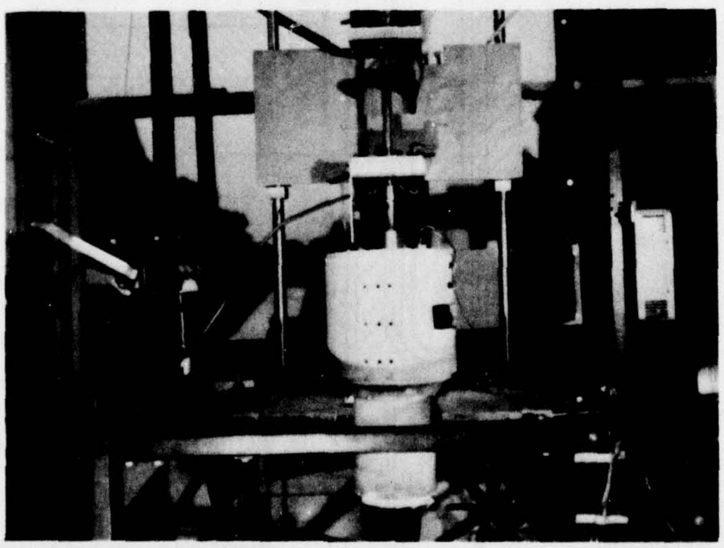


Figure 7. Schematic illustration of the high temperature continuous slurry producer.



(a)



(b)

Figure 8. Photographs of the continuous high temperature slurry producer. Top: overall view showing power supplies, recorder, and slurry producer. Bottom: close view of the Rheocasting furnace and rotation assembly.

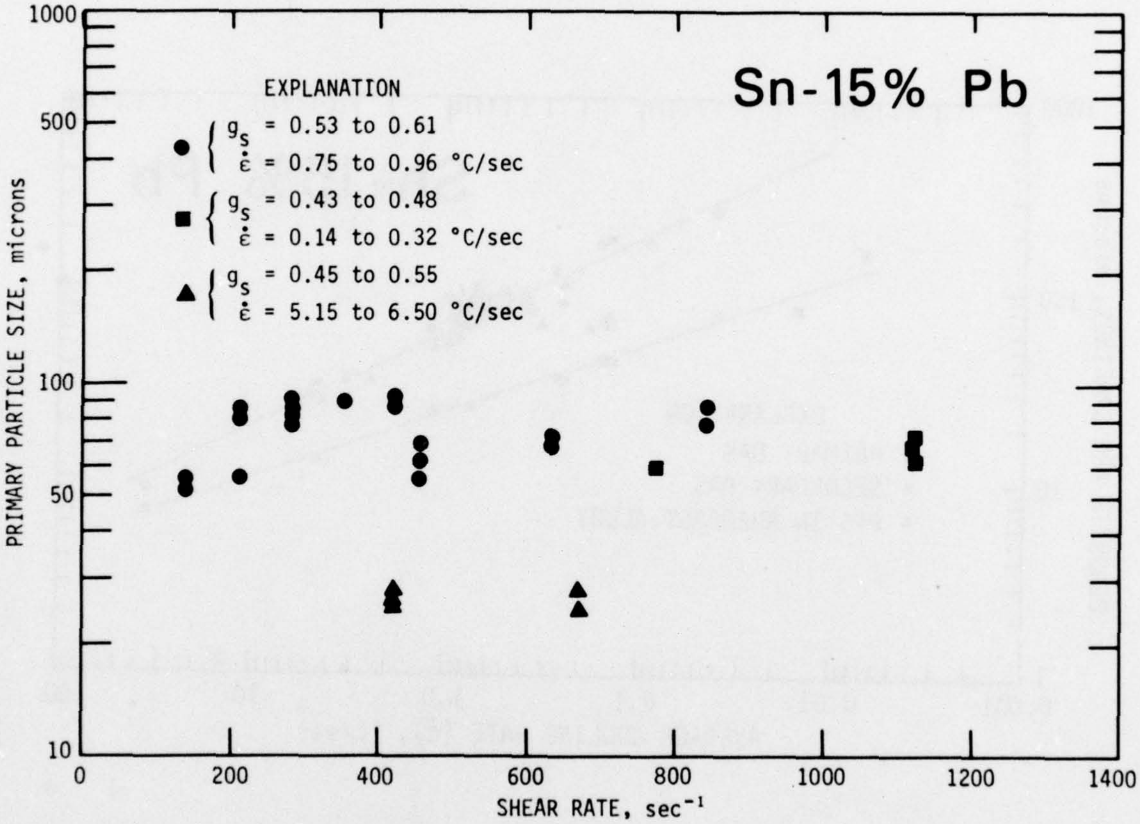


Figure 9. Primary particle size versus average shear rate in continuously produced slurries of Sn-15%Pb alloy. g_s is volume fraction solid and $\dot{\varepsilon}$ is average cooling rate during primary solidification.

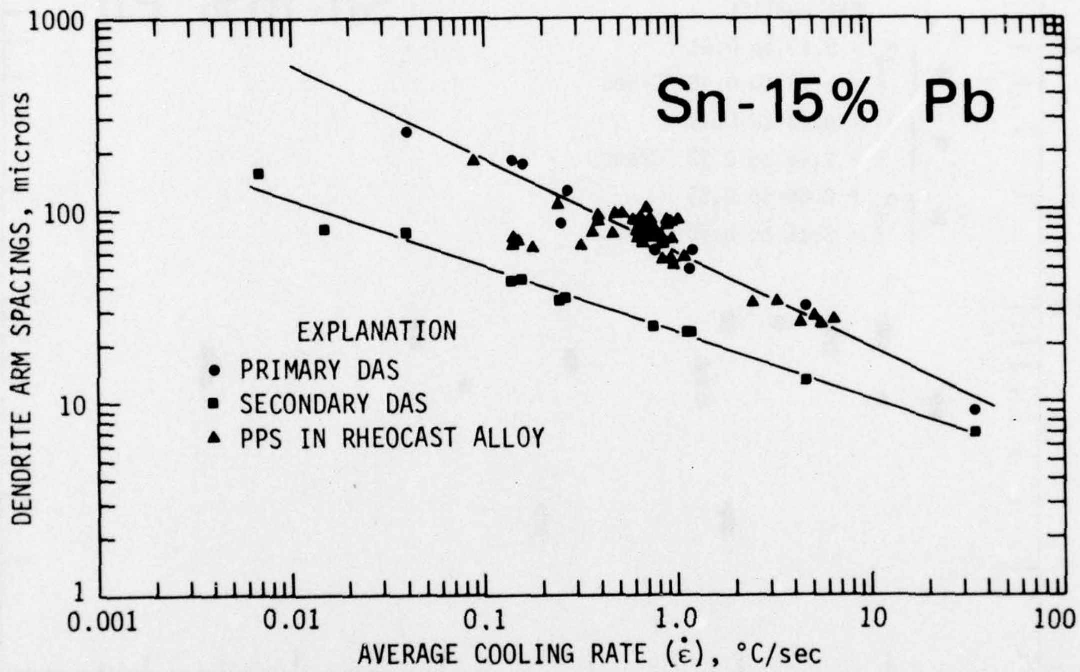


Figure 10. Variation of dendrite arm spacings, DAS, in conventionally cast, and variation of primary solid particle size, p.p.s., in continuously produced slurry of Sn-15%Pb alloy with average cooling rate during solidification.

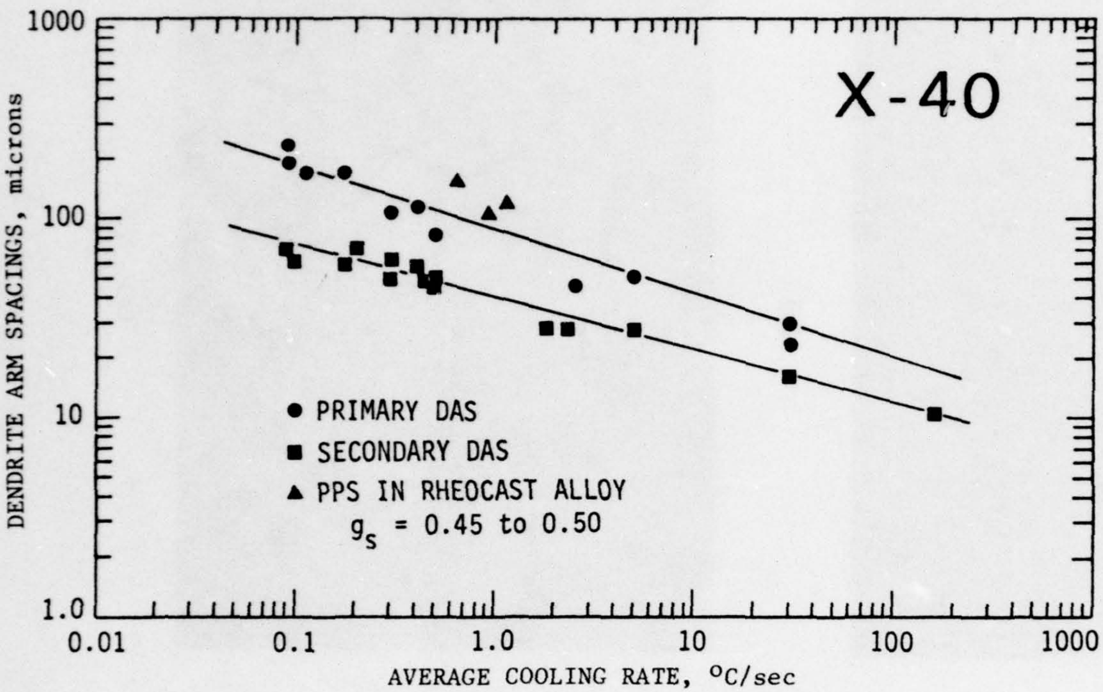
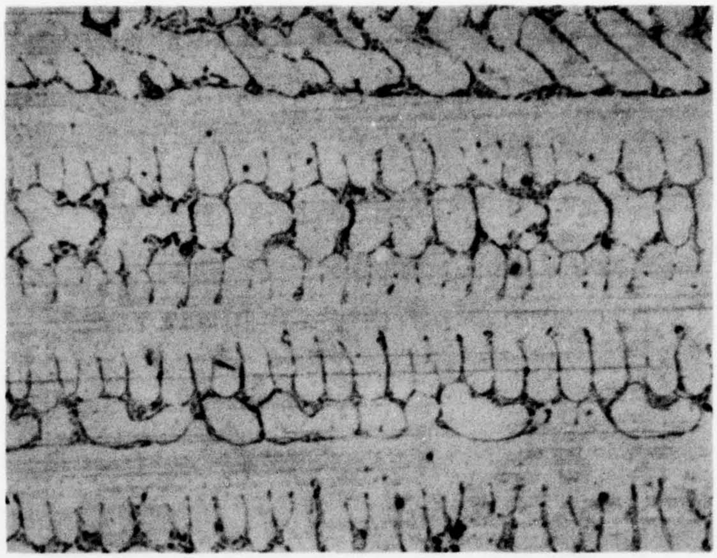
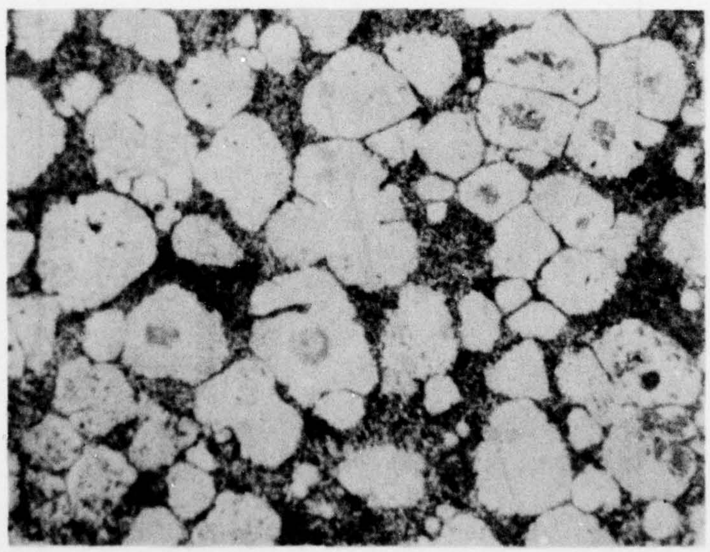


Figure 11. Variation of dendrite arm spacings, DAS, in conventionally cast, and variation of primary solid particle size, p.p.s., in continuously produced slurry of X-40 cobalt base superalloy with average cooling rate during solidification.



(a)



(b)

Figure 12. Microstructures of conventionally solidified (dendritic) and continuously Rheocast Sn-15%Pb alloy. Average cooling rate during solidification of both specimens was 1°C/sec: (a) conventionally solidified dendritic structure, (b) Rheocast structure, shear rate and volume fraction solid were 420 sec^{-1} and 0.6, respectively. Magnification 250X.

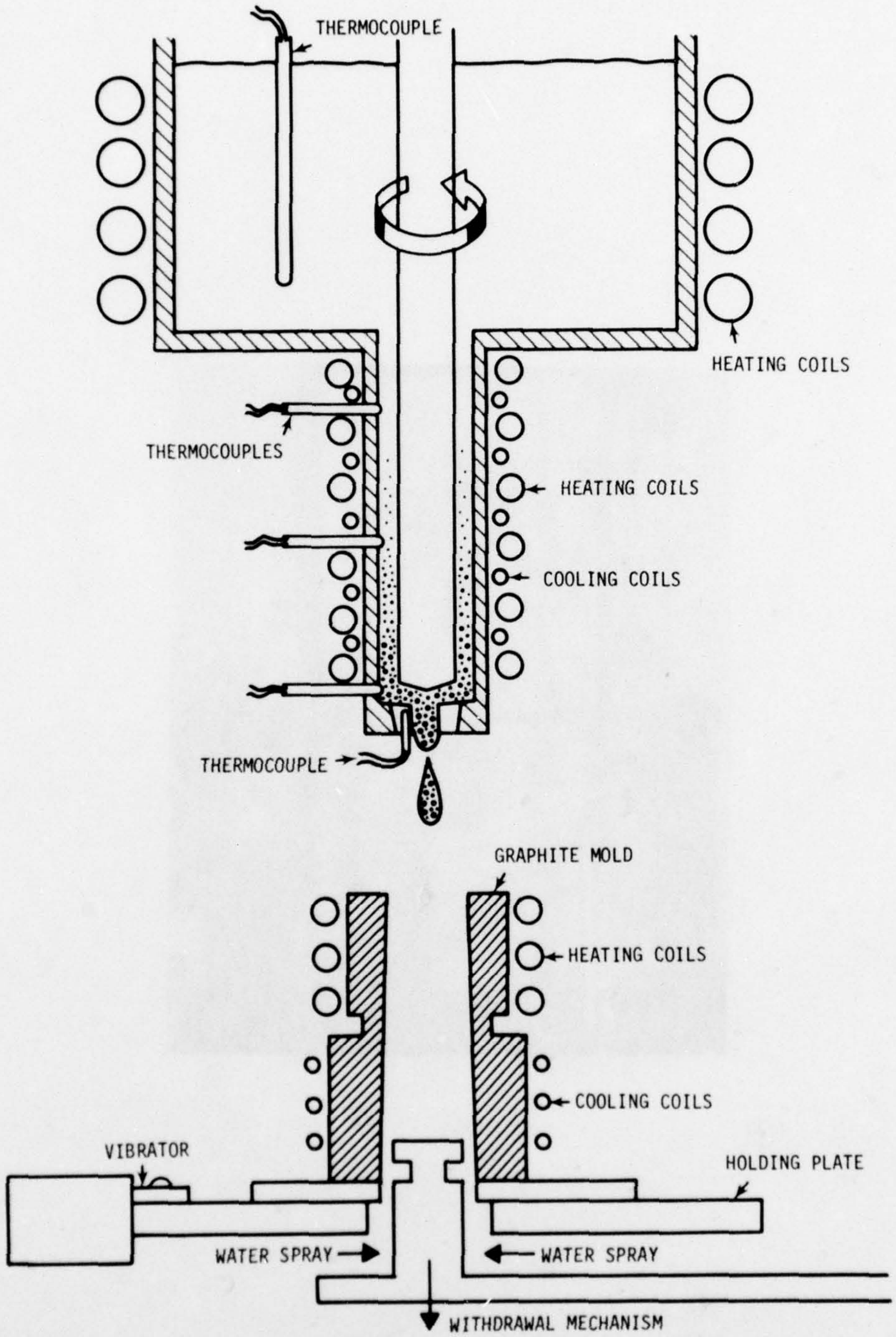


Figure 13. Schematic illustration of the low temperature continuous slurry producer and associated mold arrangement for direct chill casting of semi-continuous ingots.

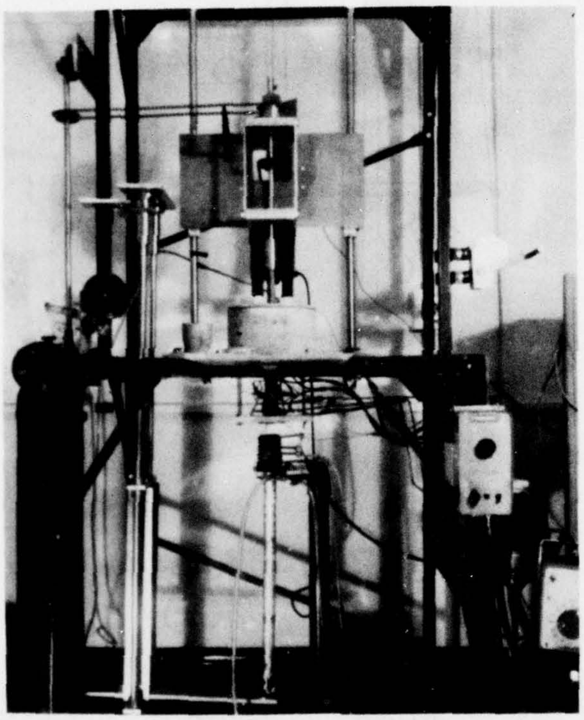


Figure 14. Photograph of low temperature slurry producer showing a Sn-15%Pb ingot in the bottom center of the photograph.

THE PRINCIPLES OF RHEOCASTING AND APPLICATION TO HIGH TEMPERATURE ALLOYS

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The broad principles underlying production of Rheocast slurries, and their flow and solidification behavior are now reasonably well understood. These principles, developed originally for tin-lead alloys, apply as well to high temperature alloys, including bronze and stainless steel.

The Rheocasting process has often been compared with ice cream manufacture. In both cases, an essential aspect of the process is to vigorously agitate the material during solidification. The resulting product is a non-dendritic fluid slurry comprising solid particles and one or more liquids. Both ice cream and Rheocast slurries are thixotropic in nature. Figure 1 shows a typical curve of viscosity of ice cream versus shear rate which is closely similar to curves obtained for Rheocast metal slurries. Rheocasting is analogous to eating ice cream as it is made, while the analog of Thixocasting is retaining

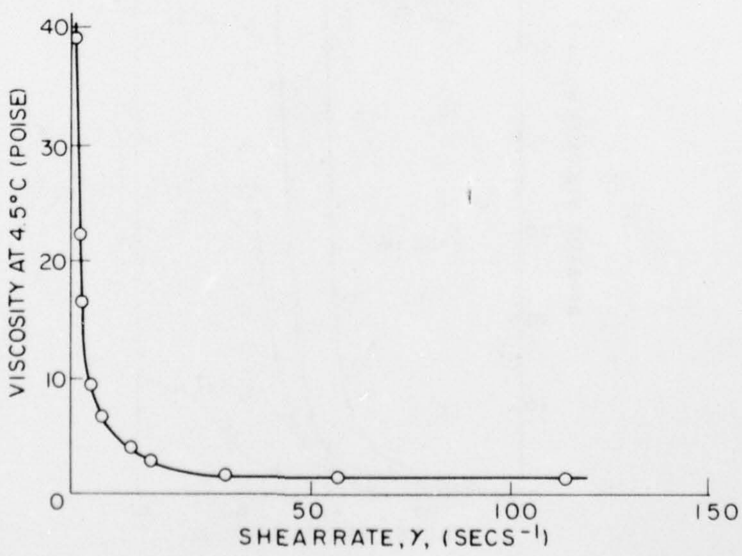

Figure 1: Viscosity of ice cream versus shear rate.

the ice cream in a deep freeze until ready to be eaten; the ice cream is then reheated until it is soft enough to eat.

Following the work of Spencer, Joly (working with Prof. Mehrabian and the writer), developed more extensive data on viscosity of semi-solid tin-lead alloys. Figure 2 shows data he gathered on viscosity as a function of fraction solid for different shear rates. Viscosity drops markedly as shear rate is increased. Generally, the viscosity increases with increasing cooling rate, as shown in Figure 3 because as cooling rate is increased, the particles tend to become less spheroidal and to become partially dendritic.

Thus, care must be taken in designing Continuous Rheocasting equipment so that cooling rate is slow enough to permit formation of the spheroidal non-dendritic solid structure. On the other hand, provided shear rate is sufficient that a non-dendritic structure can be obtained, then increasing cooling rate has the advantage that it decreases particle size as shown in Figure 4.

The above results have been verified in our laboratory on a large number of engineering alloys. For example, increasing cooling rate, at least beyond a certain minimum, has been shown to lead to dendritic or semi-dendritic structures in aluminum, bronze, 440C stainless steel and 304 stainless steel as well as M2 tool steel. An example is shown in Figure 5.

We have also begun to develop curves such as those of Figures 2 and 3 for high temperature alloys using our continuous casting machine as a viscometer. Some data obtained to date for 440C alloy are plotted in Figure 6 and show exactly similar behavior to those data plotted for tin-lead alloys in Figures 2 and 3.

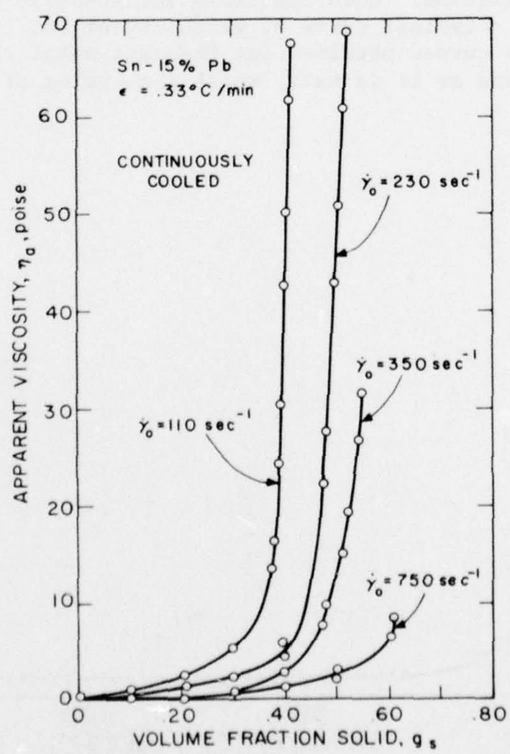

Figure 2: Viscosity of Sn-15wt% Pb alloys versus fraction solid for different shear rates (from Joly).

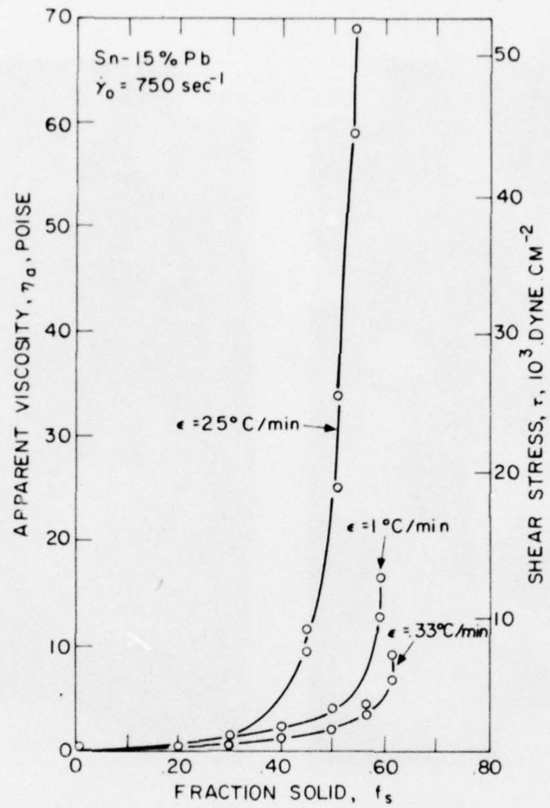

Figure 3: Viscosity of Sn-15wt% Pb alloys versus fraction solid for different cooling rates. (from Joly)

We have found, in looking at viscosities of different metals, that the curves are qualitatively always similar although they differ somewhat from alloy to alloy, as shown for example in Figure 7 which compares viscosity versus fraction solid for 440C and M2 steels.

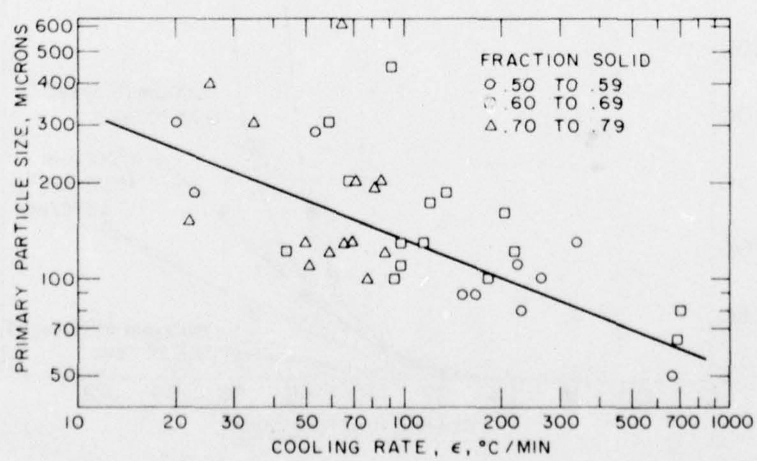

Figure 4: Primary particle size versus cooling rate - Sn-15wt% Pb alloys (from Schottman).

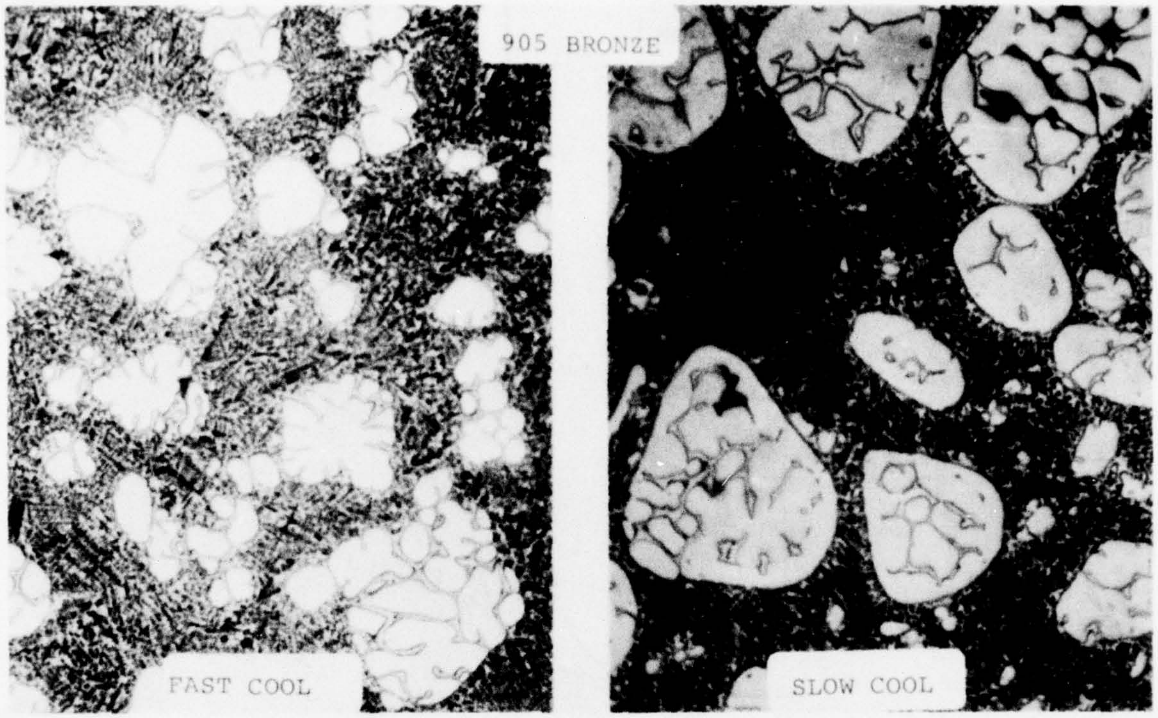

Figure 5: Microstructure of a Rheocast bronze alloy for two different cooling rates at constant shear rate.

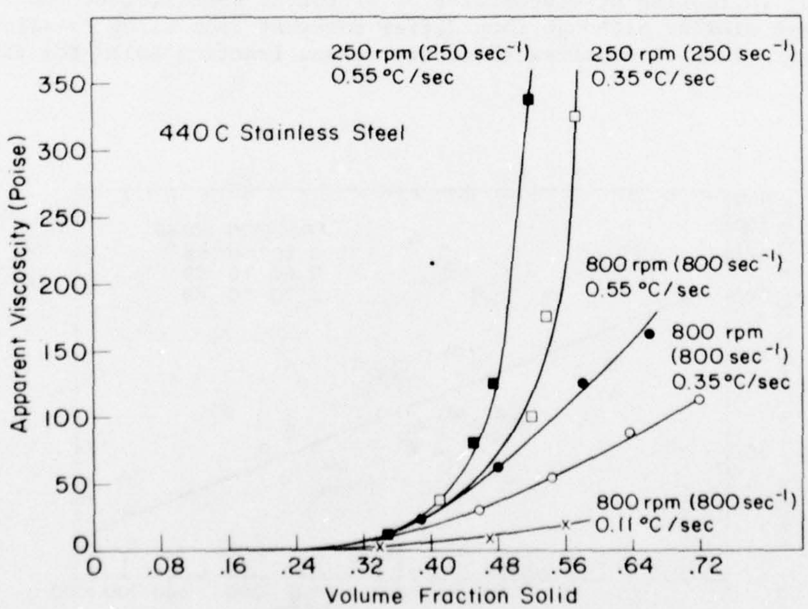

Figure 6: Apparent viscosity of Rheocast AISI 440C stainless steel versus fraction solid for different shear and cooling rates.

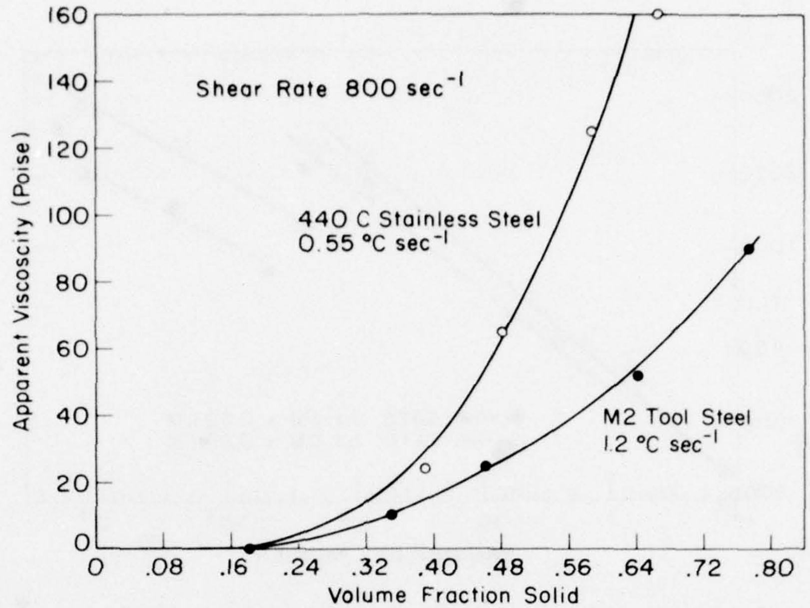

Figure 7: Comparison of apparent viscosity of Rheocast AISI 440C and M2 steels at a constant shear rate.

On reheating to a given fraction solid, the Rheocast metal alloys possess much higher viscosities at a given fraction solid than those obtained in the Rheocast metal - because of the thixotropic nature of the slurries. For example, 440C and other metals are typically heated for Thixocasting in our laboratory to about 0.5 fraction solid where the apparent viscosity (as measured by a Penetrometer test) is about 10^2 poise - that is, about the viscosity of warm butter.

The advantages of Rheocasting or Thixocasting over ordinary die casting in terms of filling behavior are described in detail in separate papers. The major advantage as far as filling goes is that the metal, being of high and controllable viscosity, can be caused to fill the die without the excessive turbulence and splashing that results when low viscosity metal is "sprayed" into dies. Work by Schottman in our laboratory has demonstrated that at the viscosities which we can obtain in semi-solid alloys, lamellar flow can be obtained through gates, in die casting. Figure 8 shows, for example, a plot of Reynolds* number versus gate velocity for experiments conducted on a small die casting machine at constant shot chamber pressure of 600 psi but with fluids of varying viscosity. The slopes of the curves at low Reynolds number (<200) are approximately one half as expected from theory. At a Reynolds number of 200 there is a discontinuous drop in Reynolds number, corresponding to the transition from lamellar to turbulent flow.

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* Reynolds number is here defined as:

$$Re = dV\rho/\mu \qquad \text{(Reynolds number)}$$

where d = hydraulic diameter of gate,
V = fluid velocity,
ρ = fluid density,
μ = fluid viscosity.

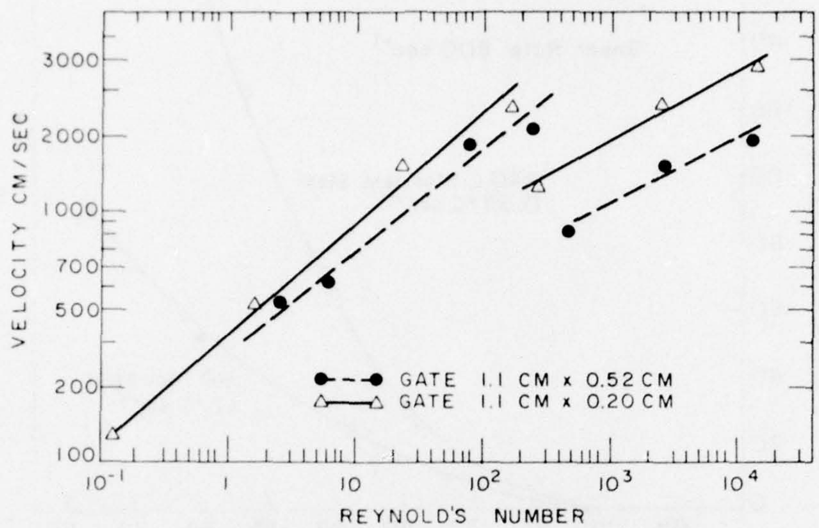

Figure 8: Ingate velocity versus Reynolds number (from Schottman).

For optimum smoothness of die filling, there is another factor to be considered and that is stability of the jet as it emerges from the gate into the casting cavity. Types of flow which have been observed as fluid emerges from the gate are: (I) "Continuous jet flow", characterized by a continuous, smooth surface on the jet; (II) "Coarse particle jet", and (III) "Atomized jet" in which the jet breaks up into very fine droplets.

Ohnesorge has shown that the type of flow can be related to the Reynolds number, and to an additional dimensionless number, Z, which includes the surface tension of the fluid.*

Data from Schottman obtained on a small die casting machine as part of this work are plotted in Figure 9, and show reasonable agreement with Ohnesorge's work, the jet flow behavior following into regions I, II, or III, depending on the dimensionless number Re and Z. Data points on these curves, from Schottman's doctoral thesis, are from oil, liquid metal, and semi-solid metal slurries.

The importance of studies such as thse to die casting of high temperature alloys such as steel is two fold. First of all, as will be shown in later papers, the soundness of castings produced is much improved by adjusting casting conditions to approach, or to be in, Region I (Region of "Continuous jet flow"). Here, air entrappment can be avoided, and excellent surface finish obtained.

A second aspect of importance relates to die life. A central thrust of much of our work at M.I.T. during the last year has been developing techniques for obtaining long die life in steel die castings. A prime requirement to do this is to reduce thermal shock to the dies or filling. Avoiding the "spraying" of hot metal against the mold as it enters is one essential step to obtaining optimum die life. A later paper discusses the die life question in detail.

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* $Z = \mu/\sqrt{\rho\sigma d}$

where: σ = surface energy of fluid.

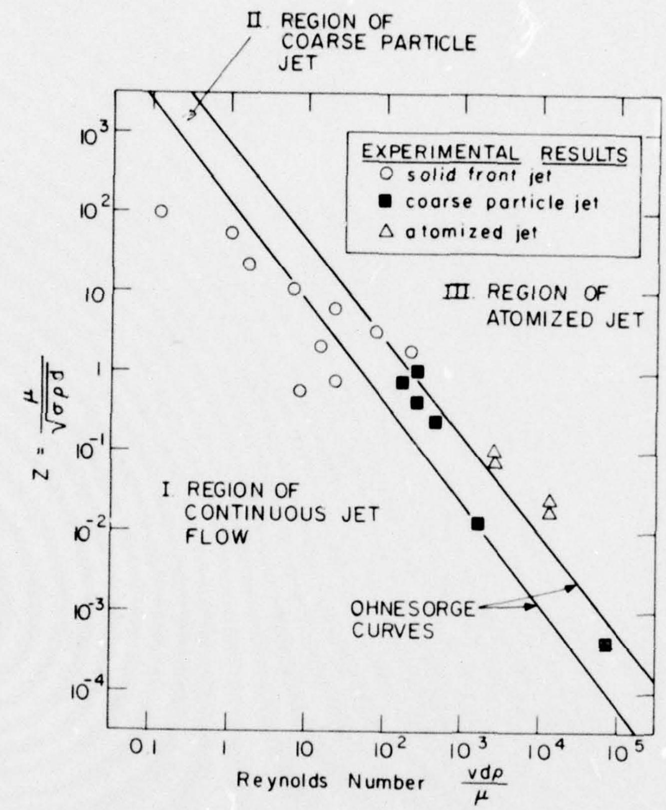

Figure 9: "Ohnesorge" plot describing jet flow character (from Schottman).

METAL-MATRIX COMPOSITES

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ABSTRACT

Metal matrix composites containing particulate and fibrous nonmetals can be prepared by introduction of the nonmetals into Rheocast slurries of aluminum alloys regardless of wetting. It is postulated that continuous agitation of the slurry brings the metal in direct contact with the nonmetal surface to permit bonding. Interface reactions between aluminum alloys containing magnesium and high-strength, high-modulus, Al_2O_3 FP fibers have been studied. A variety of other aluminum matrix composites containing particulate nonmetals were also prepared. Some of the composites possess exceptional wear properties coupled with good static mechanical properties. The composites lend themselves to casting and forming operations.

I. INTRODUCTION

Partially solidified, vigorously agitated, metal slurries not only lend themselves to various shape-forming operations, but also permit introduction and retention of fibrous and particulate nonmetals that are normally rejected (not wetted) by the completely liquid melts. This special characteristic of Rheocast slurries has been exploited to produce a variety of aluminum matrix composites heretofore not available or difficult to produce.

This paper reviews recent studies at the University of Illinois directed toward:

1. the development of aluminum matrix composite compositions for friction and wear applications.

2. the development of techniques and specific processing conditions for introduction of high-strength, high modulus, discontinuous fibers in aluminum alloy matrices to improve their mechanical properties.

3. the development of aluminum matrix composite compositions with reasonable engineering properties containing inexpensive, abundant, particulate nonmetals.

4. investigation of various shape-forming processes to produce composite components.

II. FABRICATION METHOD

The apparatus used to produce aluminum alloy composites is shown in Figure 1. The basic process for preparation of the composites utilizes the special "nondendritic" structure and rheological properties of a partially solidified, vigorously agitated, matrix alloy. The particulate or fibrous nonmetals are added to and readily retained as a dis-

persion by the partially solid alloy slurry regardless of wetting. Initially the high effective viscosity of the slurry, and the presence of a high volume fraction of primary solid in the alloy slurry prevents the nonmetallic particles from floating, settling or agglomerating. With increasing mixing times, after addition, interaction between the particles and the liquid alloy matrix promotes bonding. It is postulated that continuous agitation in the liquid portion of the slurry brings the metal close enough to the nonmetal surface to permit bond formation despite the fact that the metal does not wet the nonmetal by simple contact. The type of bond formed is peculiar to the composite system and conditions, time and temperature, of fabrication. It could be one of the five types of bonds classified by Metcalfe (3). These are: the dissolution and wetting bond, the reaction bond, the exchange reaction bond, the oxide bond, and the mixed bonds.

Composites thus prepared can be either cast when the alloy is still partially solid or after reheating to above its liquidus temperature. Both die castings and gravity fed sand castings have been made in this way (1). The composites also lend themselves to a variety of hot forming operations, such as hot extrusion (2). This latter approach can be used to align discontinuous fibers in metal matrix composites.

III. STRUCTURE AND INTERFACE REACTIONS

Figure 2 shows four examples of aluminum matrix composites containing particulate nonmetals prepared using the process described above. The nonmetals were introduced when the matrix alloy was in the slurry state. The composites were subsequently reheated to above the liquidus temperature of the alloy and cast to obtain relatively homogeneous distribution of the nonmetals in the alloy matrix.

The identification and control of interface reactions between the nonmetals and the matrix alloy are essential to successful fabrication of useful composites. A fundamental research program is presently underway in our laboratories aimed at developing aluminum alloy composites containing high strength high modulus, discontinuous fibers. Preliminary findings from our work on the aluminum alloy - Al_2O_3 FP fiber systems are presented here.

Figure 3 shows examples of interface reaction zones between discontinuous Al_2O_3 FP fibers and an Al-2%Mg alloy as a function of time at a given temperature (640°C) in the liquid-solid range. The measured thickness of the reaction zone versus square root of time after fiber addition for three different alloys are plotted in Figure 4. Note variation in reaction zone thickness with both time and alloy composition. Preliminary indications are that reaction between the Al_2O_3 FP fibers and the matrix alloys result in the formation of a spinel between magnesium oxide and aluminum oxide:

$$MgO + Al_2O_3 \rightarrow MgAl_2O_4 \qquad (1)$$

A corollary experimental program was carried out to determine the wetting characteristics of Al_2O_3 FP fibers with the completely liquid alloy melts in absence of agitation. Continuous Al_2O_3 fibers were cleaned and inserted in the melts held above their liquidus temperatures. The fibers were not wetted by the alloy matrices, and no continuous interface reaction zones were detected for times of up to two hours (see Figure 5). The above observation supports the hypothesis that agitation of a partially solid slurry brings the metal close enough to the nonmetal surfaces to permit bond formation.

The work described above is continuing. Once a better understanding of interface reaction phenomena is developed, composites of aluminum alloys containing high volume fractions of Al_2O_3 FP fibers will be prepared for mechanical property measurements.

IV. PROPERTIES OF ALUMINUM MATRIX COMPOSITES CONTAINING PARTICULATE NONMETALS

Composites of aluminum alloys containing particulate nonmetals can possess exceptional

friction and wear properties (2). Examples of wear test data obtained are shown in Figure 6. Table I lists the measured mechanical properties of some aluminum matrix composites. These composites were cast into ingots and subsequently hot extruded. Work to date indicates that careful control of interface reactions is essential if good engineering properties are to be obtained in addition to wear resistance. As example, note the wear data in Figure 6 and the mechanical properties in Table I of an aluminum alloy containing 15 wt% of 3μ size Al_2O_3 particles.

V. SHAPE FORMING

Shape forming processes such as die casting and squeeze casting are suitable for the production of metal matrix composite components. Recent work in our laboratories has been aimed at production of simple shapes using a squeeze casting apparatus. A photograph of the heated dies used and examples of the internal microstructure of two composite components produced are shown in Figure 7.

Potential applications of these composites are envisioned in components requiring improved strength, improved wear resistance or improved economy (e.g. by diluting energy expensive metals with inexpensive abundant nonmetals).

ACKNOWLEDGEMENTS

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REFERENCES

1. R. Mehrabian, R.G. Riek, and M.C. Flemings, "Preparation and Casting of Metal-Particulate Non-Metal Composites," Met. Trans., 5, p. 1899-1905 (1974).

2. A. Sato and R. Mehrabian, "Aluminum Matrix Composites: Fabrication and Properties," Met. Trans B, 7B, p. 443-451 (1976).

3. A.G. Metcalfe, Composite Materials, A.G. Metcalfe, Editor, Academic Press, I, p. 67-121 (1974).

TABLE I

Mechanical Properties

Material	0.2% Y.S. (KSI)	U.T.S. (KSI)	El. (%)
Al-4Cu-1Mg	33	52	26
+ 10% SiC irregular particles and whiskers	48	57	8
+ 15% fine Al_2O_3 wedge-shaped particles	44	58	13
+ 5% synthetic K-mica flakes	35	52	26
Al-4Si-1Mg	27	34	14
+ 5% SiC particles + 5% synthetic mica	21	26	5

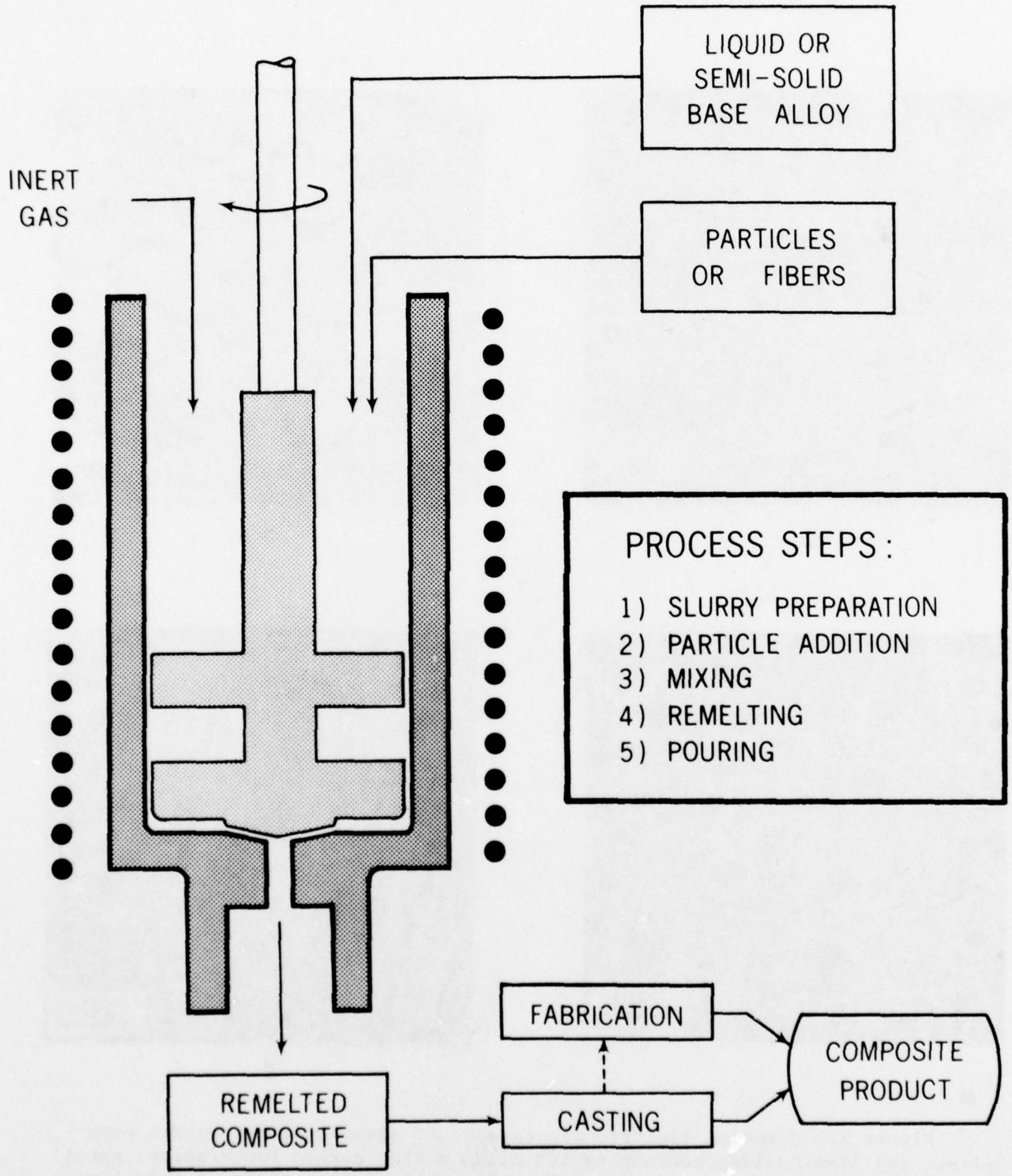


Figure 1.- Schematic of the apparatus for fabrication of aluminum matrix composites.

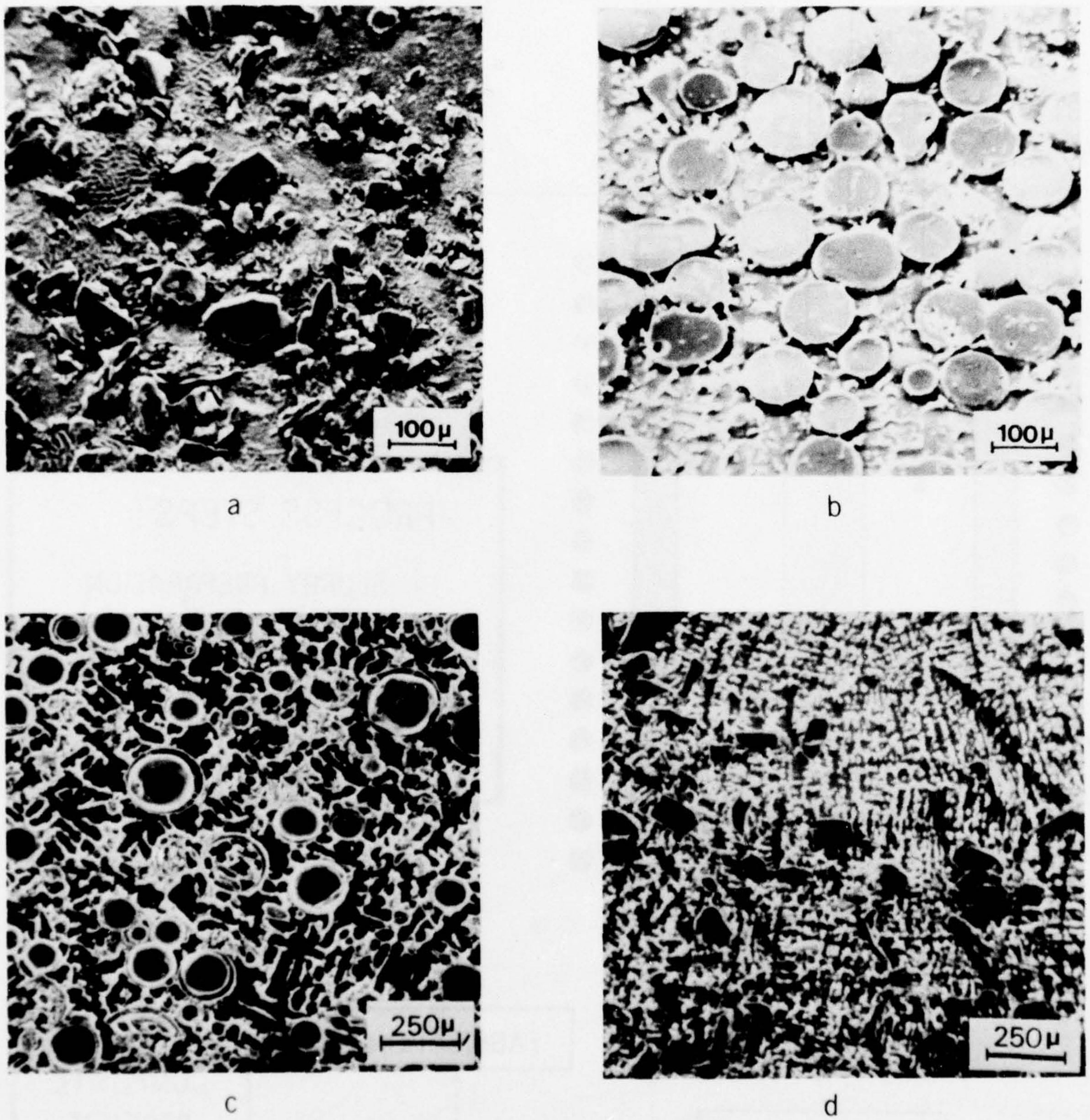
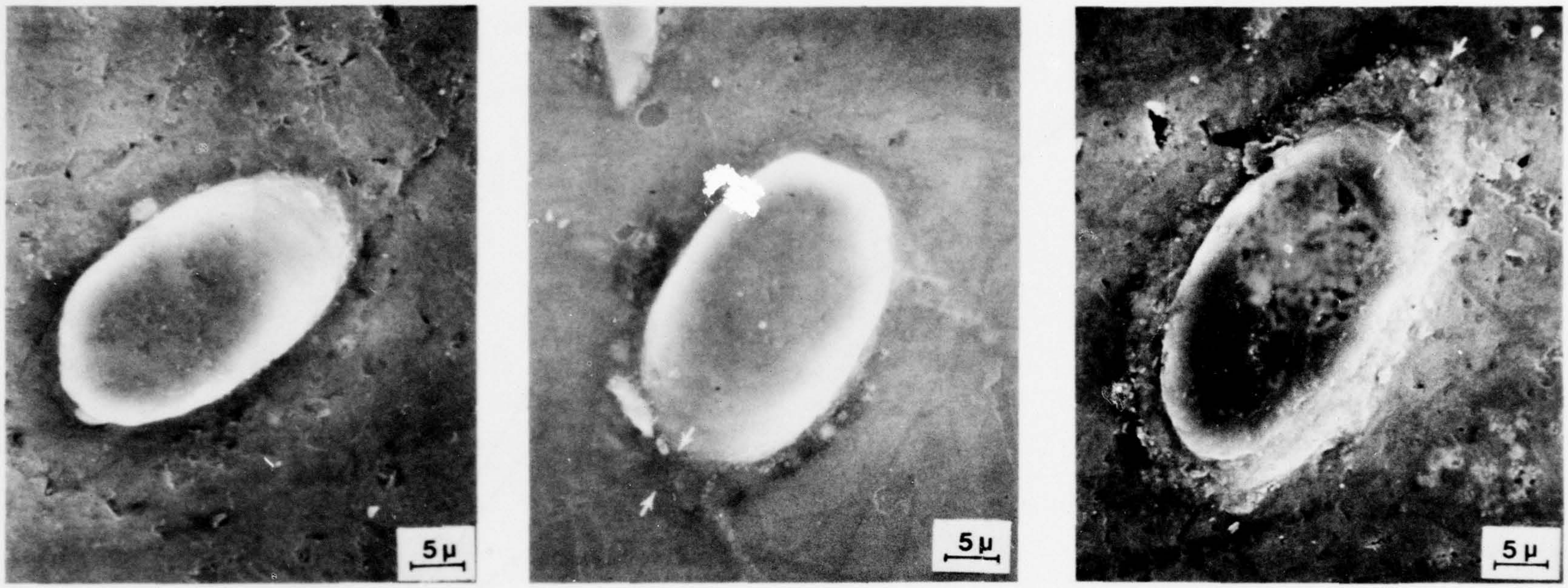


Figure 2.- Scanning electron micrographs of aluminum alloy matrix composites. (a) Al-4%Cu-1%Mg containing 10% of 75 m size carbon (anthracite) particles, (b) Al-4%Cu-1%Mg containing 30% of 100 m size glass beads, (c) Al-4%Si-1%Mg containing 20% of 50-150 m size cenospheres and (d) Al-4%Cu-1%Mg containing 10% of 125 m size silica sand particles.



a b c

Figure 3.- SEM views of reaction zones with increasing time in Al-2%Mg alloy containing Al_2O_3 FP fibers. The composite was produced when the alloy was in the partially solid state, (T = 640°C). -- (a) t = 1 min., (b) t = 30 min., (c) t = 120 min.. Arrows show extent of interface reaction.

Figure 1: Viscosity of ice cream versus shear rate.

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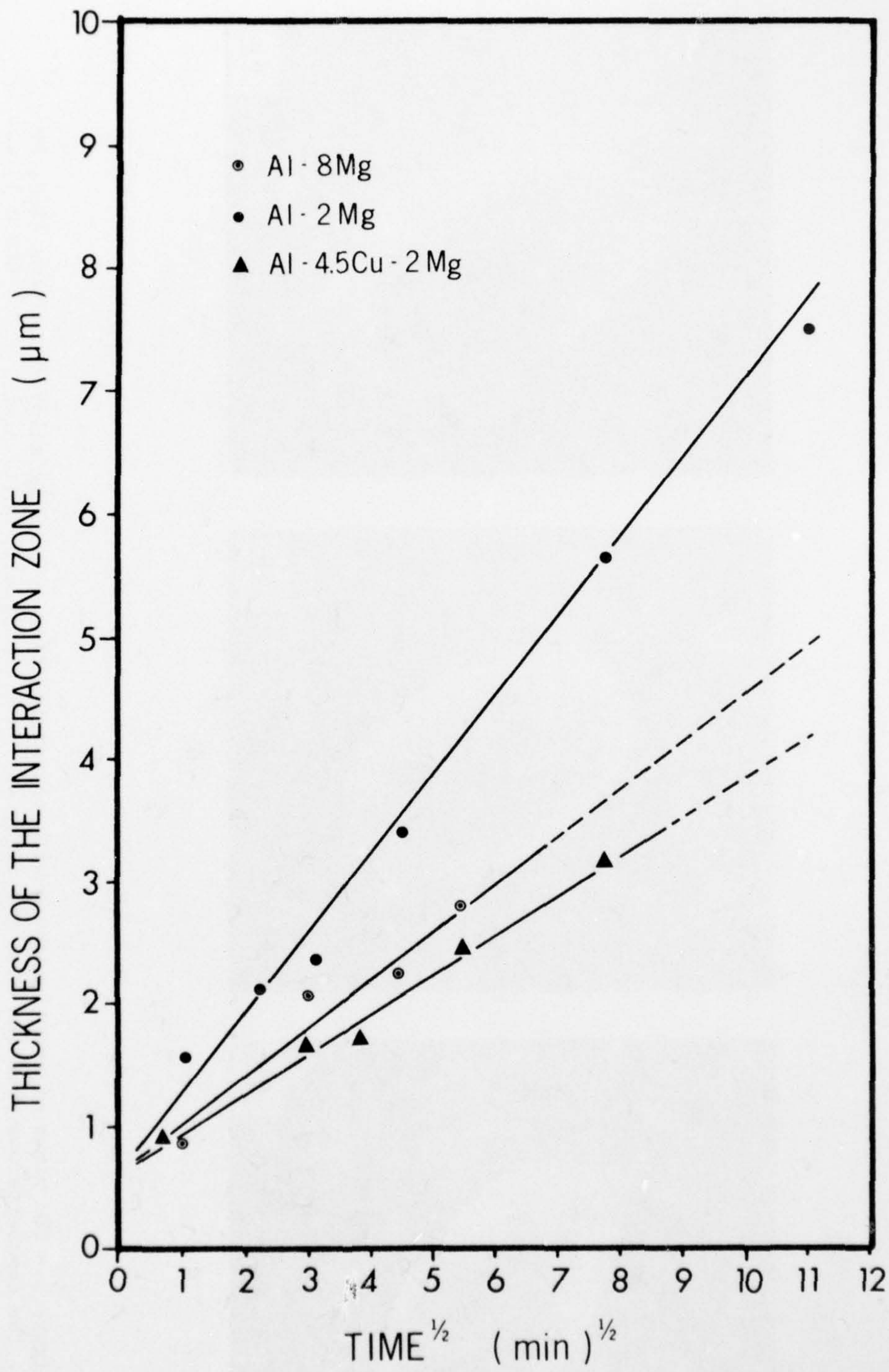


Figure 4. Thickness of the interaction zone vs. square root of time after addition of Al_2O_3 FP fibers in different partially solid aluminum alloy slurries.

Figure 5.- SEM viewgraphs of Al_2O_3 FP fibers inserted into a completely liquid melt of Al - 8% Mg alloy. Note that originally spaced fibers were pushed together, infiltration did not occur and no continuous reaction zone is observed after 1 hr - at 630°C.

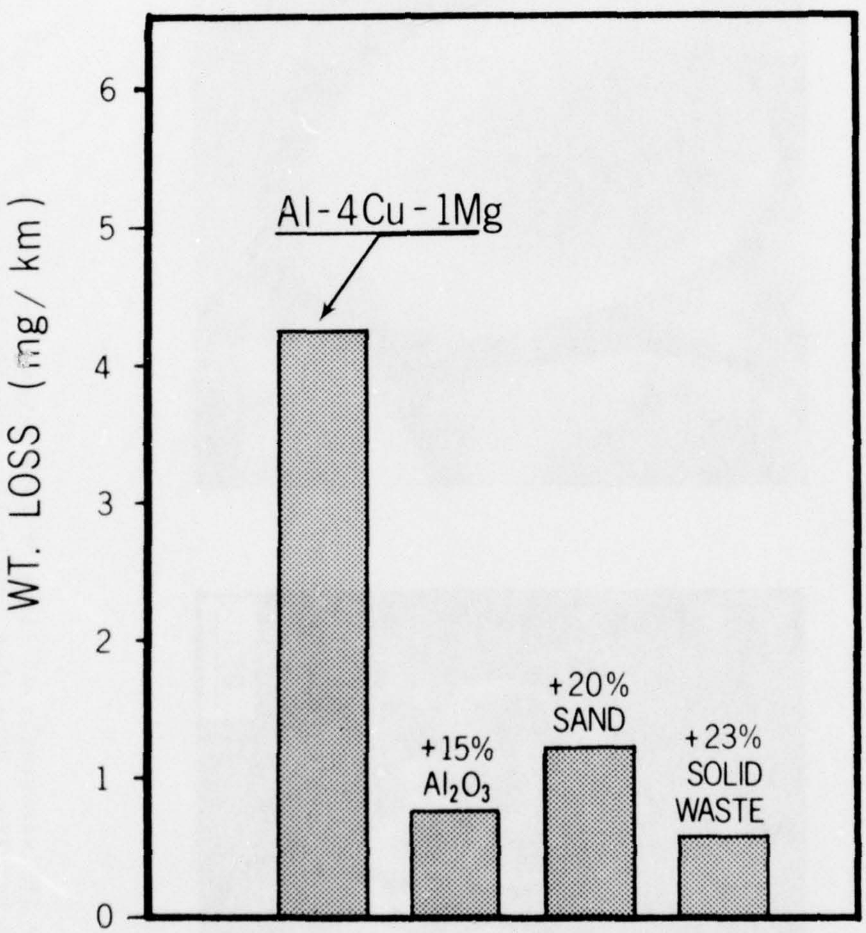
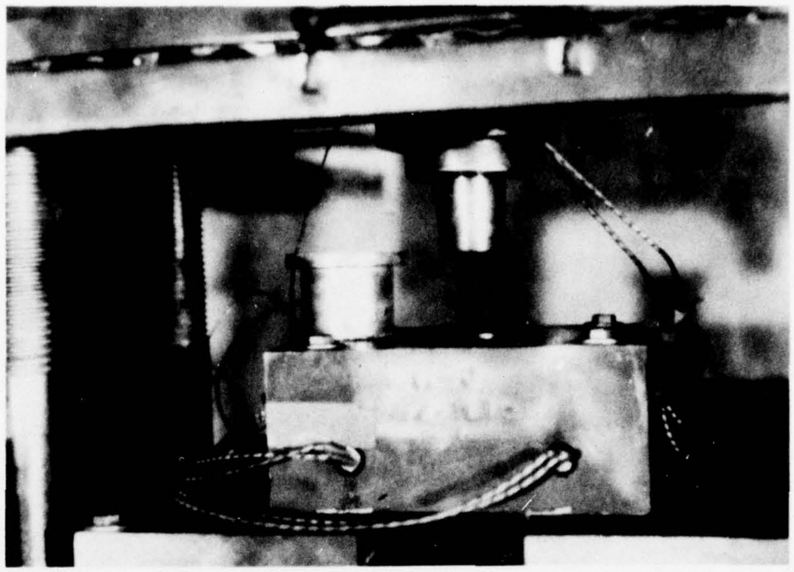


Figure 6. Weight loss measured during wear testing of aluminum alloy (Al-4wt%Cu-1wt%Mg) matrix composites containing (a) 15wt%Al_2O_3, (b) 20wt% silica sand and (c) 23wt% solid waste particles.



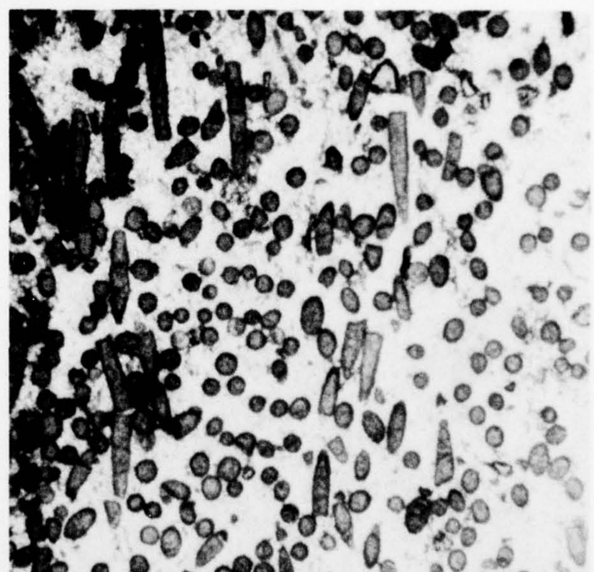


Figure 7. Photograph of the squeeze casting apparatus for fabricating components from aluminum matrix composites. Bottom photographs are the microstructure of composite parts; left -- aluminum alloy plus SiC particles; right -- aluminum alloy plus Al_2O_3 fibers. Magnification 100X.

SESSION III

SECONDARY PROCESSING

Session Chairman

A. Bement
Defense Advanced Research Projects Agency

THIXOCASTING DEVELOPMENT

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SUMMARY

The Thixocasting process for high temperature alloys has been developed from model studies of the rheological character of semi-solid Rheocast alloys. A high temperature Continuous Rheocaster has been designed which can produce ferrous alloy slurries with high fraction solid at rates up to 5 lb. min^{-1}. Many thousands of test Thixocastings have been produced in a variety of ferrous and other high temperature alloys.

The Thixocasting process, shown schematically in Figure 1 is the most developed of a group of allied processes (e.g., Compocasting, Thixoforging) which exploit the unique rheological characteristics of semi-solid Rheocast alloys. It consists of three basic steps: (1) Continuously Rheocasting ingot stock, (2) Reheating to the semi-solid range individual charges cut from the ingots, and (3) casting the reheated charges to near net shape.

The basis for the development of Thixocasting lies in early fundamental studies at M.I.T. on the rheology of semi-solid model Sn-Pb alloys. This work, discussed in detail in associated papers, showed how the application of vigorous shearing to a solidifying melt (Rheocasting) could produce semi-solid alloy slurries with a unique microstructure. Thus, in contrast to the rigidly interlocked dendritic arrays of conventional alloys, the microstructure of Rheocast alloys consisted essentially of isolated solid spheroids suspended in the remnant liquid. Such slurries were shown to remain highly fluid when more than 50% solidified.

Furthermore, Rheocast alloy slurries were shown to be thixotropic in that their apparent viscosity was both time and shear rate dependent. A slurry could thus be produced which contained more than 50% solid with a viscosity of less than 10 poise (such as heavy machine oil); subsequent isothermal holding (without further solidification) without shearing however would cause the apparent viscosity to rise to many hundreds or thousands of poise (to the consistency of butter for instance 10^6 - 10^7 poise at room temperature) in relatively short times.

The major results from this early work, which form the basis for the engineering development of Thixocasting are summarized in Figures 2 and 3. The apparaent viscosity of a Rheocast alloy slurry is thus a function of cooling rate, shear rate and volume fraction solidified. Furthermore, both the size and shape of the primary solid particles (formed in the Rheocaster) were shown to be dependent on cooling rate. Faster cooling producing finer particles (Figure 4) but for any given shear rate (degree of agitation) creating a tendency to revert to a dendritic microstructure. Increasing shear rates were shown to promote rounder more spheroidal primary particles.

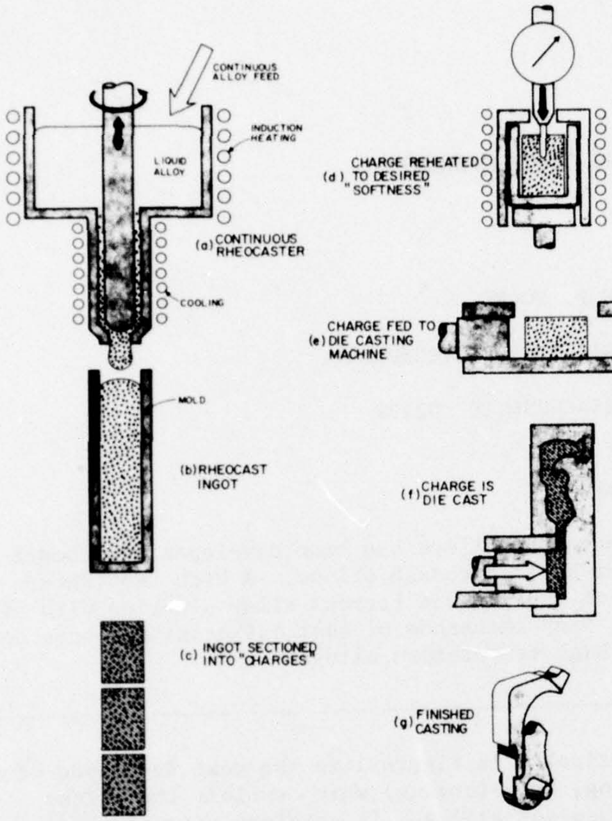

Figure 1: The Thixocasting Process.

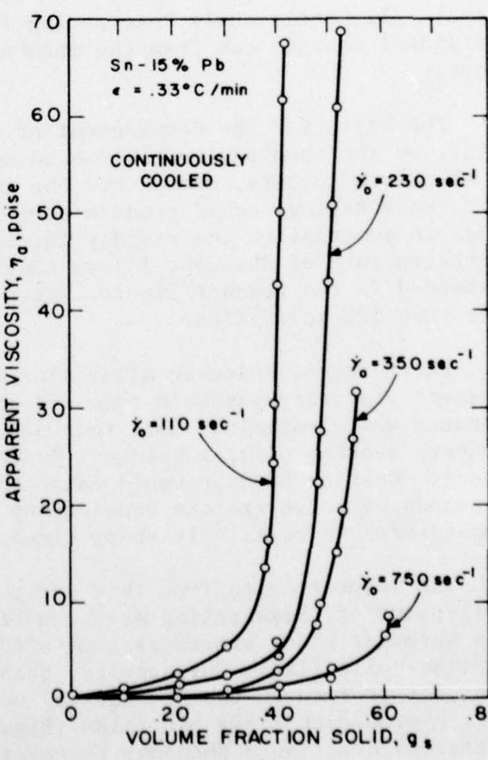

Figure 2: Apparent viscosity of continuously cooled Sn-15wt% Pb alloys versus volume fraction solid for different shear rates (from Joly).

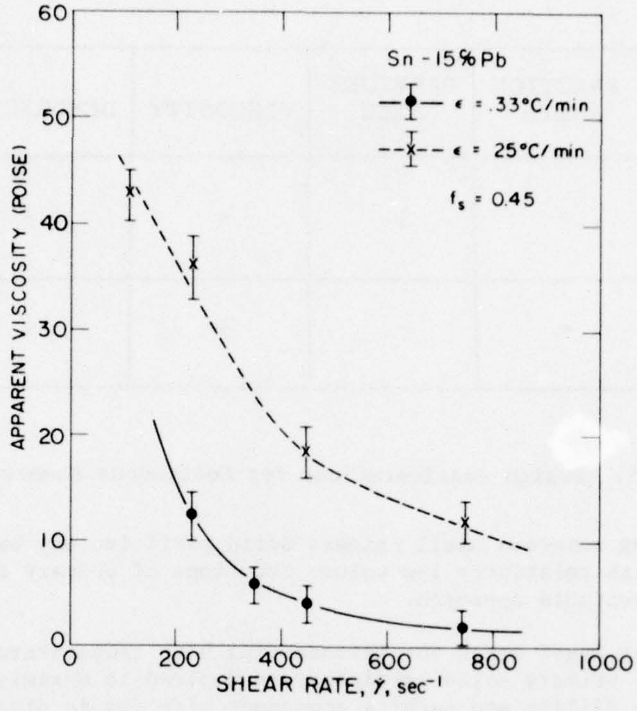

Figure 3: Apparent viscosity of Sn-15wt% Pb alloy at 0.45 volume fraction solid versus shear rate for two different initial cooling rates (from Joly).

This study on model alloys therefore emphasizes the design considerations for a Continuous Rheocaster to be used in production. These are summarized in Figure 5.

Clearly, the design for a Continuous Rheocaster will be dictated to a large extent by the intended application of the product. Thus, to exploit the grain refining advantages of Rheocasting in the manufacture of large ingots or castings a relatively high throughput

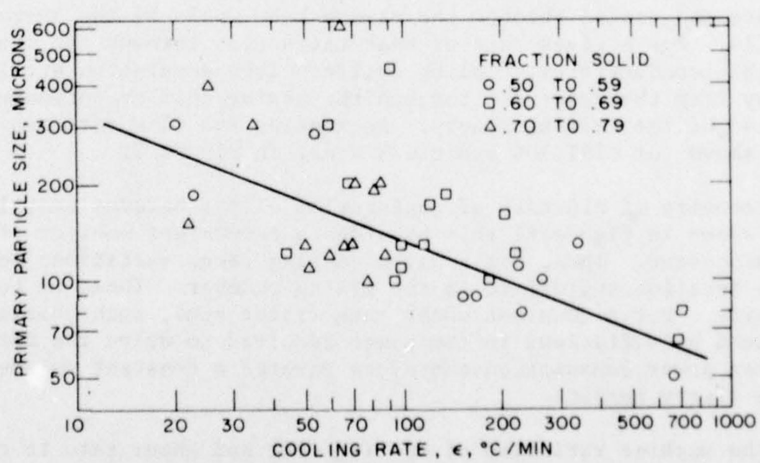

Figure 4: Primary particle size versus cooling rate for Sn-15wt% Pb Continuously Rheocast (from Schottman).

	FRACTION SOLID	PARTICLE SIZE	VISCOSITY	DENDRICITY	THROUGH-PUT
COOLING RATE ↑	↑	↓	↑	↑	↑
SHEAR RATE ↑	-	-	↓	↓	-

Figure 5: Design considerations for Continuous Rheocasting.

rate of slurry containing numerous small primary solid particles may be desired. High cooling rates coupled with relatively low volume fractions of primary solid particles to act as nuclei may be a suitable approach.

In the production of ingot stock for Thixocasting high temperature alloys, however, high volume fractions of primary solid particles are desired to maximize the advantages with respect both to die filling and machine component life (as is discussed in associated papers). The design of the Continuous Rheocaster employed in the pilot plant development of Thixocasting of ferrous alloys at M.I.T. is shown schematically in Figure 6.

The Continuous Rheocaster consists essentially of two vertically connected, concentric cylinders. An upper reservoir chamber holds about 40 pounds of molten alloy at about 30°C superheat. Beneath this, a smaller diameter chamber, lined with recrystallized alumina functions essentially as a heat exchanger and agitation zone. Shearing is provided by a recrystallized alumina rotor which passes through the reservoir chamber and mixing chamber. This rotor also functions as a valve on a small exit port at the base of the mixing chamber. Rheocast slurry is produced continuously by allowing alloy to flow through the mixing chamber where it is simultaneously sheared by the action of the rotor in the small annular space and cooled through the mixing tube walls by the surrounding water cooled copper coils. For a given rate of heat extraction through the crucible walls (a function of crucible conductivity, cooling coil/crucible separation etc.) increasing the flow rate of alloy from the reservoir through the mixing chamber decreases the volume fraction solidified of the exiting slurry. Decreasing the flow rate has the opposite effect. This is shown for AISI 304 stainless steel in Figure 7.

Since the viscosity of slurries of engineering alloys behaves exactly as the model Sn-Pb alloys (as shown in Figure 8) this provides a convenient monitor of the output from the Continuous Rheocaster. Thus, for a given cooling rate, variations in flow rate will effect the volume fraction solidified in the mixing chamber. These in turn will effect the slurry viscosity. For a constant shear rate (rotor rpm), such changes in slurry viscosity are sensed by variations in the power required to drive the rotor. Maintenance of a constant rotor power consumption therefore ensures a constant volume fraction solidified in the slurry output.

As well as the machine variables of cooling rate and shear rate to consider in the design of a Continuous Rheocaster there are also considerations of materials compatability. Thus to construct a Continuous Rheocaster to produce bronze alloys, a range of materials such as graphite, and mullite, are feasible. In the design of a Continuous Rheocaster for Thixocasting ferrous alloys however, recrystallized alumina has proven to be the only

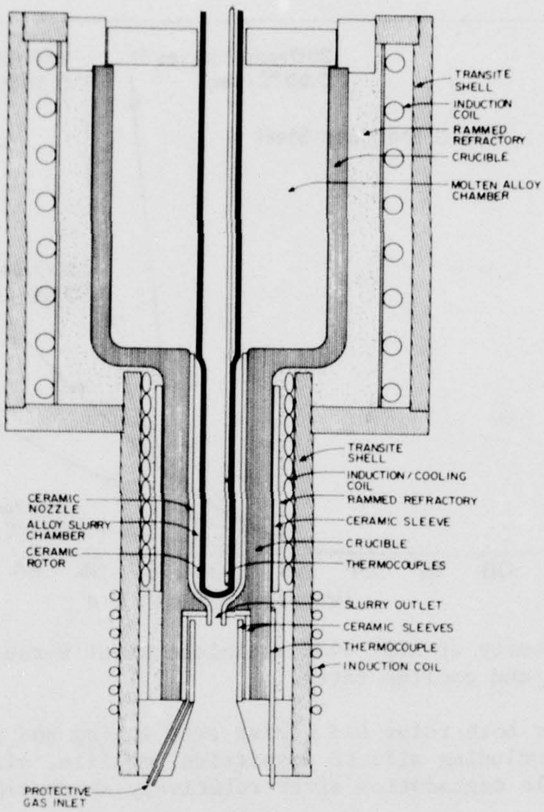

Figure 6: Schematic of the High Temperature Continuous Rheocaster.

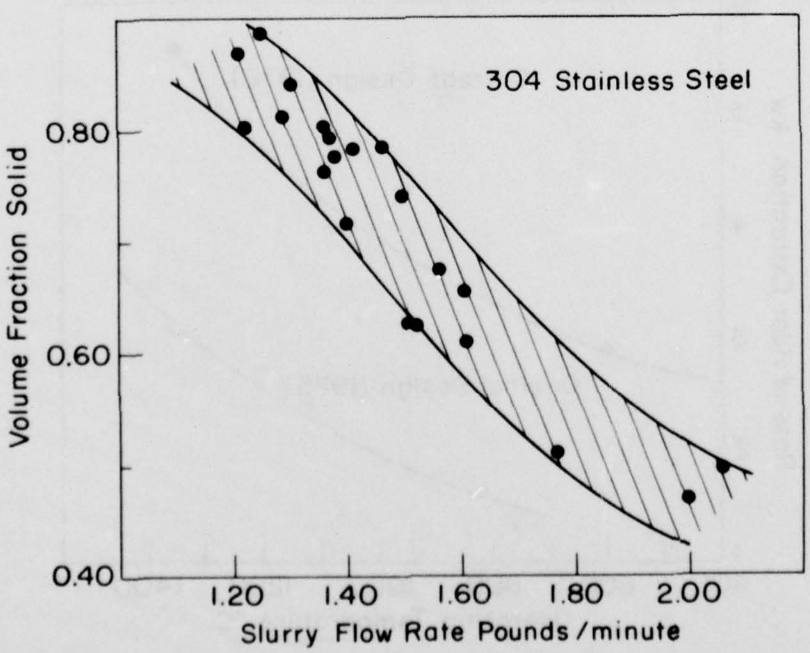

Figure 7: Volume fraction primary solid versus slurry flow rate for a given rate of heat extraction from the mixing chamber.

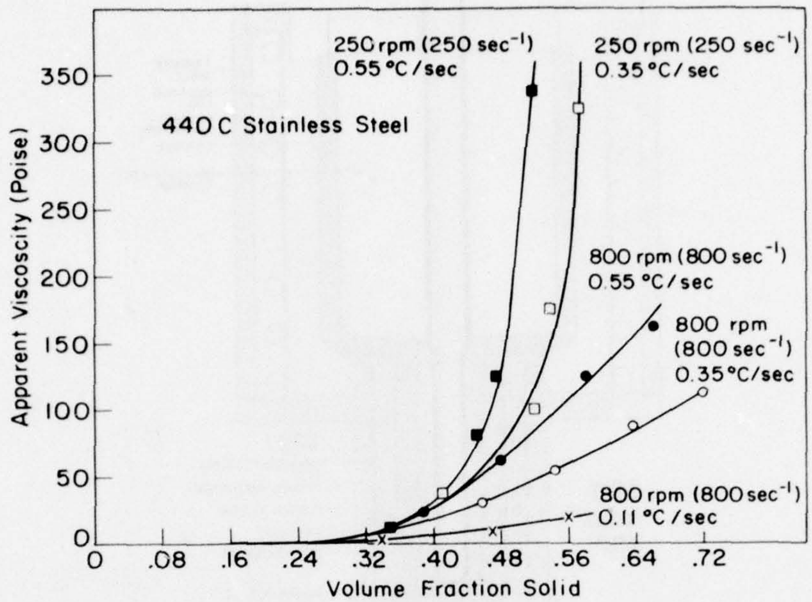

Figure 8: Apparent viscosity of AISI 440C stainless steel versus volume fraction solid for various shear and cooling rates.

satisfactory material for both rotor and mixing tube lining and provides long service life. *Other materials including silicon oxynitride, mullite, silicon nitride and cermets* are subject to intolerable degradation after relatively short exposure to the melt.

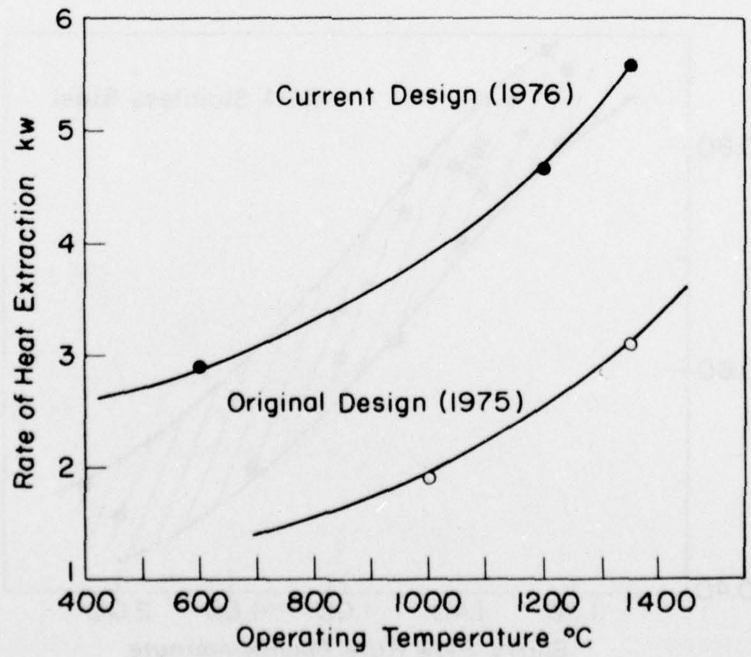

Figure 9: Rate of heat extraction versus mixing chamber operating temperature for the High Temperature Continuous Rheocaster at M.I.T.

The Continuous Rheocaster at M.I.T. has thus evolved by the optimization of design (Figure 9) to the point at which continuous runs of up to 500 pounds of stainless steel are routine at rates up to 5 pounds per minute.

This machine has to date produced several tons of a variety of ferrous alloys as well as aluminum alloys, bronzes and superalloys. A typical microstructure of a droplet quenched directly into water is shown in Figure 10. In this, the light areas represent the primary solid particles formed within the Rheocaster and the fine dendritic matrix is the liquid portion which froze rapidly at the time of the quench.

In the Thixocasting process, the Continuously Rheocast slurry is teemed directly into ingot molds (or continuously cast) in which the final freezing rate, unlike the water quenched drops, approaches that of the Rheocast portion. A typical fine grain microstructure from an ingot of AISI 440C is shown in Figure 11. In this, the slower cooling rate in the ingot has produced a dendritic structure that is comparable in size to the primary solid particles. Thus the different regions of Rheocast and dendritic freezing are difficult to distinguish structurally.

However, the primary solid particles are inherently of different composition to the matrix structure by virtue of the segregation of solute elements which occurs in solidification. Thus they will possess higher melting points than the matrix which upon reheating will melt first allowing reclamation of the Rheocast microstructure. Variations in both the ingot cooling rate and the reheating rate are therefore important variables to consider in Thixocasting. These stages will influence the degree of post-Rheocasting homogenization which occurs and can therefore be optimized with respect to final Thixocast structures. For instance, relatively slow cooling and reheating rates will provide homogenization and permit the primary solid fraction to be Thixocast fully solutionized.

In the Thixocasting system at M.I.T. the M16 rifle hammer has been the test part. Small sections of the ingots 1-1/4" diameter by 1-1/1" long are cut to form individual charges. These charges are then inductively reheated without agitation to the semi-solid

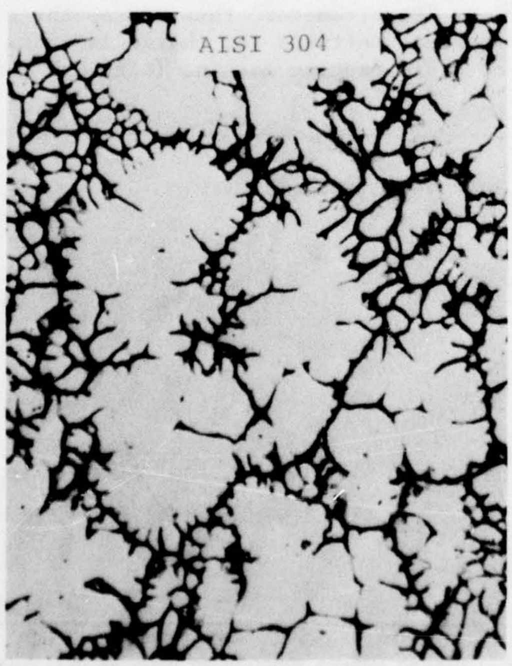

Figure 10: Microstructure of a quenched droplet of Continuously Rheocast AISI 304 stainless steel. Approx. X60.

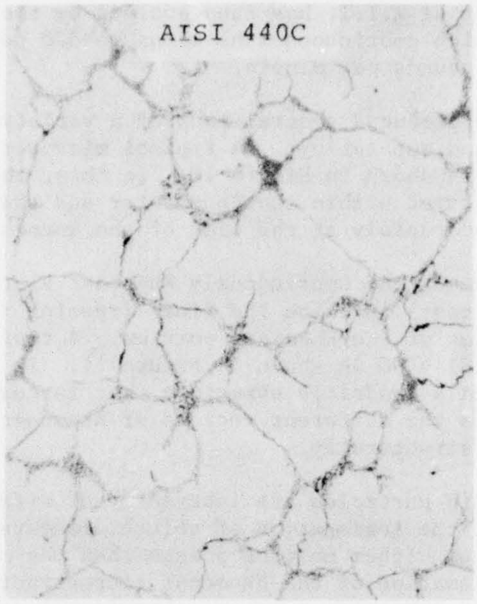

Figure 11: Ingot microstructure of Continuously Rheocast AISI 440C stainless steel. Approx. X60.

range in an automatic reheat station. During reheating a small 1/8" diameter alumina probe impinges on the charge (which is contained in a clay graphite crucible) and progressively penetrates. The probe is driven by an air cylinder at constant pressure and for a given reheating rate and depth of penetration, the force on the probe correlates well with volume fraction solid at the charge, Figure 12.

This "Softness Indicator" or "Penetrameter" thus senses the consistency or viscosity of the charge, and at the appropriate softness the charge is cast. It is transferred manually to the shot chamber of a die casting machine (although that could of course be

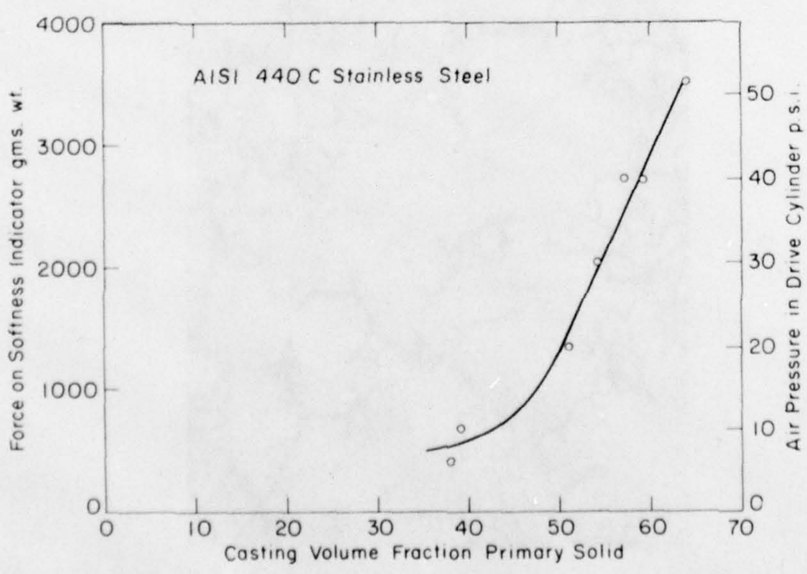

Figure 12: Operating curve for the Softness Indicator.

automated) as a soft-solid with a viscosity typically 10^7 poise (much like butter for instance). The shearing which occurs as the alloy enters the die then lowers the viscosity of the charge to the point at which it flows smoothly to fill the cavity.

The die caster therefore has the advantage in Thixocasting that both the machine variables such as injection velocity and pressure may be reduced since the material cast is more viscous than fully liquid metals and fills the die more smoothly and also that the charge viscosity may be adjusted. This may be accomplished by changing the volume fraction solidified of the charge at casting, the primary particle size or the shearing rate.

The regimes for obtaining acceptable Thixocastings of the M16 rifle hammer in AISI 440C stainless steel cast at 0.50 volume fraction solid into steel dies at 275°C may be mapped out as in Figure 13. Clearly as injection velocities are decreased below a certain minimum incomplete die filling results. At excessively high velocities unacceptable air entrapment results. The regime for acceptable castings, based upon both surface quality and internal soundness lies at injection velocities which are low in comparison to typical conventional aluminum or bronze die casting practice.

Many thousands of the M16 rifle hammer test part have been made in the Thixocasting system at M.I.T. Primarily the two stainless steels AISI 440C, 304 have been cast but smaller quantities of parts in aluminum alloys, bronzes, superalloys and other ferrous alloys such as M2 tool steel have been made.

The quality of such parts has been monitored both by visual and radiographic inspection. The improved soundness of castings which results from the improved cavity filling and reduced solidification shrinkage is shown by the results of inspection of 300 parts Thixocast in AISI 304 stainless steel, Figure 14. A radiographic rating of one in this histogram (in which most parts fall) represents an almost clear radiograph.

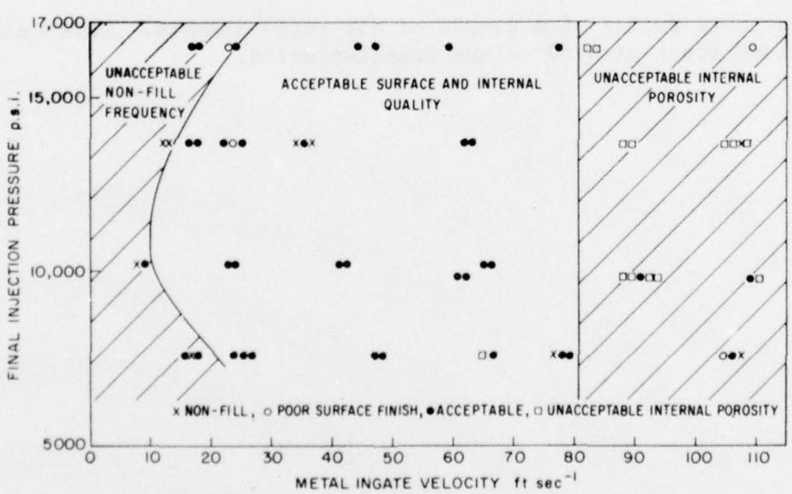

Figure 13: Thixocasting parameter optimization for the M16 rifle hammer cavity. AISI 440C stainless steel Thixocast of 0.50 volume fraction solid.

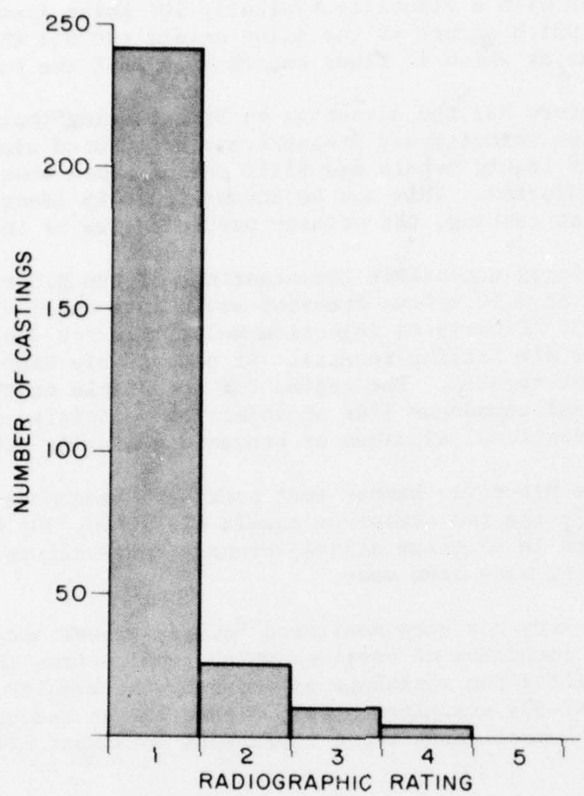

Figure 14: Radiographic rating of a sample of M16 rifle hammers. Thixocast AISI 304 stainless steel at 0.50 volume fraction solid.

DIECASTING STUDIES – DIE FILLING BEHAVIOR OF RHEOCAST METALS

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ABSTRACT

Machine casting studies have been conducted to determine the effects of casting variables, gate geometry, charge viscosity (volume fraction of solid), and gate velocity on die filling characteristics. To accomplish this, a laboratory casting machine, incorporating transparent dies, has been used to directly observe the nature of fluid flow during die filling. Experimental results indicate that at low filling velocities, high viscosity fluids (partially solid alloys) fill the die cavity with a stable front with a minimum amount of air entrappment. At higher gate velocities and with lower charge viscosity, atomized and transitional die fill are observed. The transition of die filling mode can be correlated to three dimensionless numbers, the Reynolds number, the Weber number, and the Z number, which incorporate the material and design parameters.

I. INTRODUCTION

The die casting of high quality components free of porosity and defects requires an understanding of the relationship between the casting process parameters and the fluid flow patterns which develop during die filling. The important process parameters include (i) the geometry of the gate and runner system, (ii) the gate velocity, and (iii) the kinematic viscosity (fraction solid) of the charge material. These parameters determine the mode of die filling (solid front, transitional, or atomized) and the amount of air entrappment and vorticity present within the die cavity. Each of these phenomena influence the quality of the cast part.

In order to study the relationship between casting parameters and fluid flow characteristics, a laboratory casting machine, fitted with a transparent die half, has been built to permit direct observation and photography of the fluid flow patterns which develop during die filling. This apparatus has been used to conduct numerous experiments where organic fluids and partially solid Sn-Pb alloys, with a range of kinematic viscosities, have been cast using different gate geometries and velocities. In the following sections, both the apparatus and the experimental results will be described.

II. LABORATORY CASTING MACHINE

The laboratory casting machine shown in Figure 1 was designed to simulate a commercial horizontal cold chamber die casting machine. It is specially equipped to permit direct observation and photography of fluid flow during die filling. The machine consists of a split die, a locking mechanism, plunger and shot sleeve assembly, and a hydraulic power supply.

The dies are fabricated from mild steel plate and one die half houses a flat ground quartz window through which high speed movies are taken during die fill. Two distinct die cavities were used in these studies: (a) a flat plate die cavity, and (b) a simulated turbine blade die cavity. These die cavities and the runner and ingate pattern employed are shown in Figures 2 and 3.

The shot piston of the casting machine is powered by a Reed Prentiss hydraulic system capable of 2000 psi pressure. This power supply has two accumulator tanks and controls to vary both injection pressure and speed. Metal injection velocities at the gate range from a few feet per second to over 250 per second.

During operation, either controlled viscosity fluids or Sn-Pb alloys (liquid or partially solid) are fed into the shot sleeve. During the casting of the low temperature alloys, the shot sleeve is heated by a controlled power supply. High speed motion pictures are taken during die fill using a 16 mm Fastex Movie Camera capable of film speeds of up to 7000 frames per second. The camera is activated by an automatic timer connected to a switch on the piston rod.

III. EXPERIMENTS AND RESULTS

A large number of experiments were conducted during which the machine casting parameters were varied. The process variables examined include:

(1) the kinematic viscosity of the charge material (.003 to 23.0 cm^2/sec, Stokes)
(2) the gate velocity (100 to 8000 cm/sec $\sim$2 to $\sim$250 ft/sec)
(3) gate and runner geometry, and location

The effect of charge kinematic viscosity was studied by casting various organic fluids and Sn-Pb liquid and partially solid slurries. The liquids used and their physical properties are listed in Table I. Both casting cavity designs were investigated.

The results of experiments conducted to date with both the plate die and the turbine blade die show that the kinematic viscosity of the charge and the ingate velocity influence the pattern of fluid flow emanating from the ingate. Qualitatively, it was found that at low velocity, high viscosity fluids fill the die cavity with a stable front as shown in Figure 4. However, as ingate velocity increases and charge viscosity decreases, the charge/air interface becomes unstable and atomization of charge occurs at the ingate. At intermediate values of velocity and viscosity, a transitional mode of filling is observed. These die filling patterns are shown in Figure 4.

Physically, the system parameters which influence the stability of the charge/air interface and hence the mode of die filling include

(1) charge viscosity, ν
(2) charge surface tension, σ
(3) ingate velocity, V
(4) charge density, ρ
(5) ingate geometry, a, b

In order to succintly examine the quantitative influence of these parameters, they can be combined into dimensionless groups. The characteristic dimensionless numbers which result from combining the material and design parameters are the Reynolds number, R_E, the Weber number, W, and the Z number, Z, where:

$$R_E = \frac{VD}{\nu} \quad (1)$$

$$W = V\sqrt{\rho D/\sigma} \quad (2)$$

$$Z = \frac{W}{R_E} = \nu\sqrt{\rho/\sigma D} \tag{3}$$

In these equations, D represents the hydraulic diameter which is related to the ingate thickness, a, and width, b, by the following equation:

$$D = 4\,\frac{\text{gate area}}{\text{wetted perimeter}} = 4\,\frac{a \cdot b}{a + b} \tag{4}$$

By representing the mode of die filling observed during each experiment on a plot of Reynolds number, R_E, versus either the Z number or the Weber number, the quantitative relationship between process variables and flow regime can be established. These plots, determined from experiments conducted to date with various fluids, in both of the casting cavity designs, and several runner geometries are shown in Figures 5 and 6. On these plots Regions I, II, and III represent the range of parameters during which solid front fill, transitional fill, and atomized die fill are achieved, respectively. These results confirm the qualitative results described above. For example, from the plot of Reynolds number versus Z number, Figure 5, at a constant value of $Z = 1$, we find that solid front fill is observed when $R_E < 50$ and atomized fill is obtained when $R_E > 300$. At intermediate values of Reynolds number transitional die filling occurs. By definition, a low Reynolds number is synonymous with low gate velocities and high values of kinematic viscosity.

In general, when the die fills with a solid front, air entrappment is minimized within the casting cavity. The minimization of porosity occurs because during the gentle fill, air within the cavity is pushed ahead of the advancing fluid front and escapes through the air vents into the overflows. However, when die filling is accompanied by atomization or transitional flow, air is entrapped within the die cavity and both turbulence and vorticity is observed.

During die filling of the flat plate cavity, the flow patterns and the final porosity distribution are both complex at high Reynolds number. At early stages of filling, flow separation occurs along the inside wall of the fan gate, Figure 4c, generating a vortex which is sustained until filling is complete. At this time, gases entrapped within the fan gate rise into the casting cavity. Also, because the gating system employs two gates, a large amount of turbulence develops due to the mutual impingement of flow from each ingate at high values of Reynolds number. The atomized jets from each ingate finally impact against the forward wall and the fluid rebounds along the outside walls in a direction opposite the incoming jet. This flow pattern continues and two additional vortices and associated gas pockets are observed within the cavity. During the machine casting of metal alloys, early blockage of the air vents prevents the escape of the air entrapped in both the ingate and the die cavity. Typical flow patterns are shown in Figure 7.

During filling of the simulated turbine blade casting, the flow patterns are similarly complex. Three distinct gating patterns were studied to determine the design which will provide the best casting quality. The following gating systems were investigated:

1. transverse filling with three ingates located along the side of the blade.
2. longitudinal filling with one ingate located at the shouldered end of the blade.
3. longitudinal filling with die ingate located at the reduced end of the blade.

A considerable amount of air was entrapped when the simulated turbine blade was gated by either the first or the second gate configuration. However, the third gating pattern enabled die filling to proceed with a minimum of entrapped gases. At low gate velocities, high viscosity charge filled the die in a solid front manner. Photographic sequences taken during die filling are shown in Figure 8.

The results of the experiments conducted with the transparent casting system, have shown that the mode of die filling and the amount of gas entrapped during filling are controlled by the physical properties of the charge material and the geometry and location of

the ingates. Specifically, reduced porosity, turbulence, and vorticity are observed when the cavity fills with a solid front. This condition of filling is established at low Reynolds numbers and hence with a low ingate velocity and with charge material having a high kinematic viscosity.

The apparent viscosity of partially solidified slurries of metal alloys increases with increasing volume fraction of solid. Therefore, it is anticipated that as the volume fraction of solid in the charge material increases, solid front fill can be achieved at relatively high gate velocities. Experiments to date with partially solid slurries of Sn-15%Pb alloy verify the above.

ACKNOWLEDGEMENTS

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TABLE I

Transparent Casting System
Injected Fluids

Material	Density (gm/cc)	Viscosity (Stokes)	Surface Tension (Ergs/cm^2)
Methanol	0.7924	7.55×10^{-3}	23
Hi-Vac Standard 0.1	0.879	0.78	28
Hi-Vac Heavy 0.1	0.880	3.23	32
Glycerine	1.26	11.92	63.4
S-600 Viscosity Standard	0.889	22.97	36.3

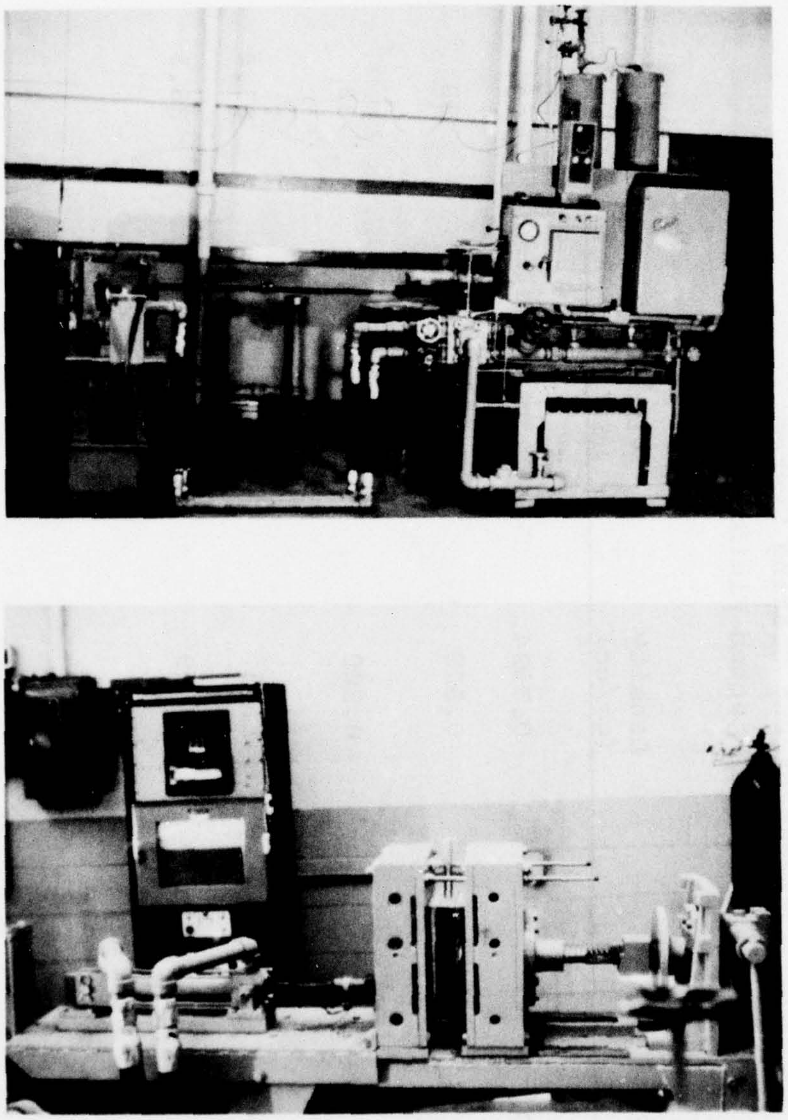


Figure 1 Photographs of the laboratory casting machine used to study flow phenomena during die filling.

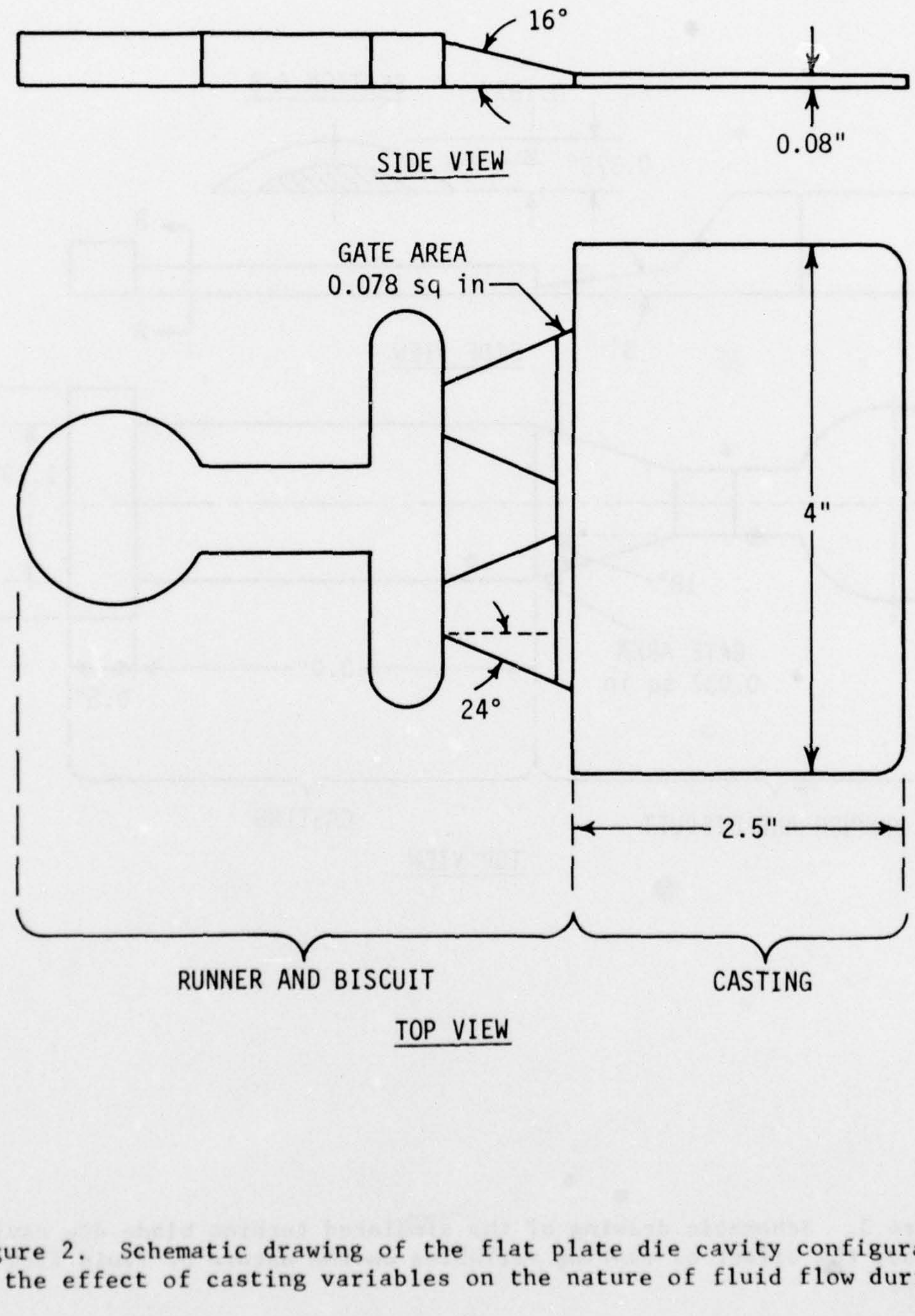


Figure 2. Schematic drawing of the flat plate die cavity configuration used to study the effect of casting variables on the nature of fluid flow during die filling.

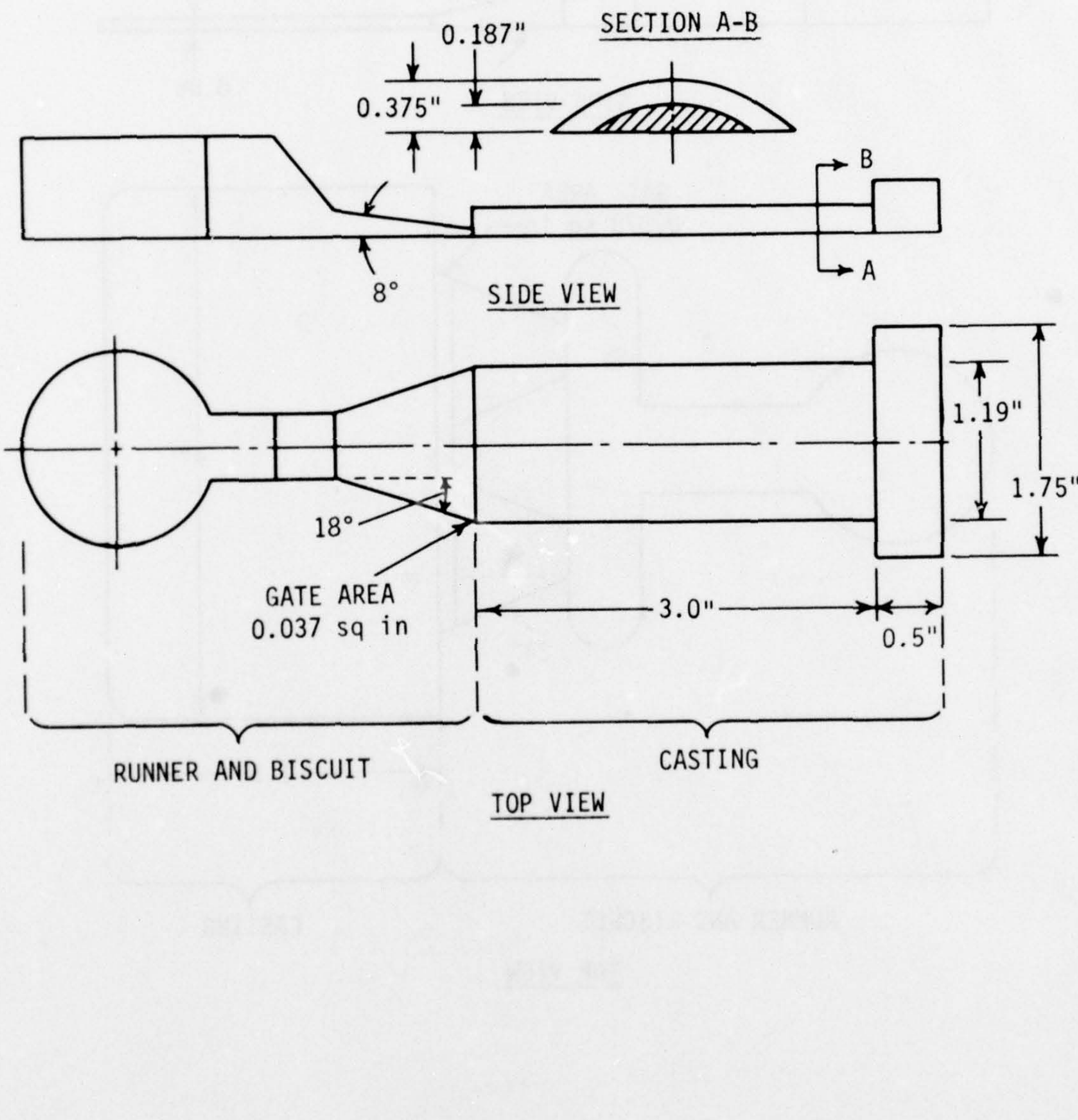
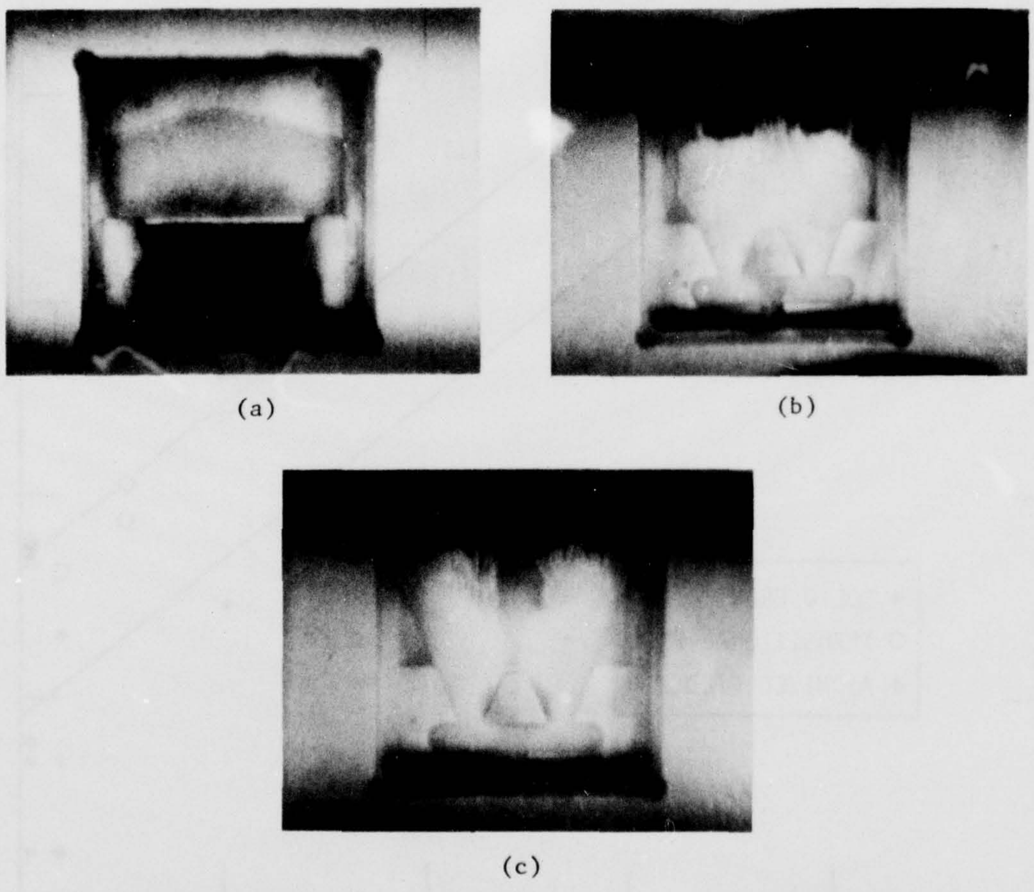


Figure 3. Schematic drawing of the simulated turbine blade die cavity used to study the effect of casting variables on the nature of fluid flow during die filling.



(a) (b) (c)

Figure 4. Photographs showing the three modes of filling for the flat plate die cavity. (a) solid front fill of S-600 standard viscosity fluid at an ingate velocity of 12 feet per second; (b) transitional fill of standard HV oil at an ingate velocity of 100 feet per second; and (c) atomized fill of standard HV oil at an ingate velocity of 150 feet per second.

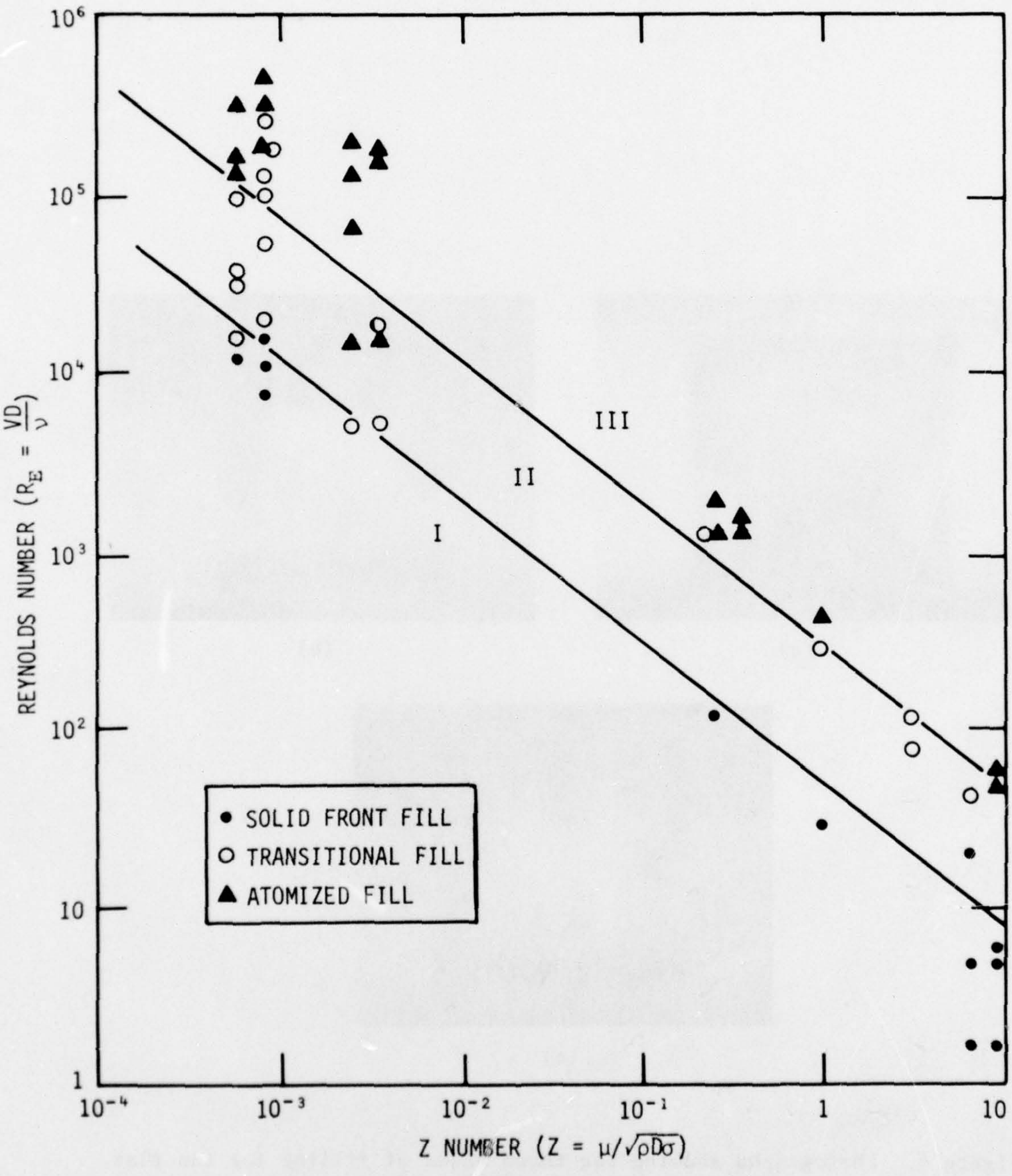


Figure 5. Experimental data obtained in the laboratory casting machine presented in terms of the Reynolds number versus the Z number. This plot permits prediction of the mode of die filling.

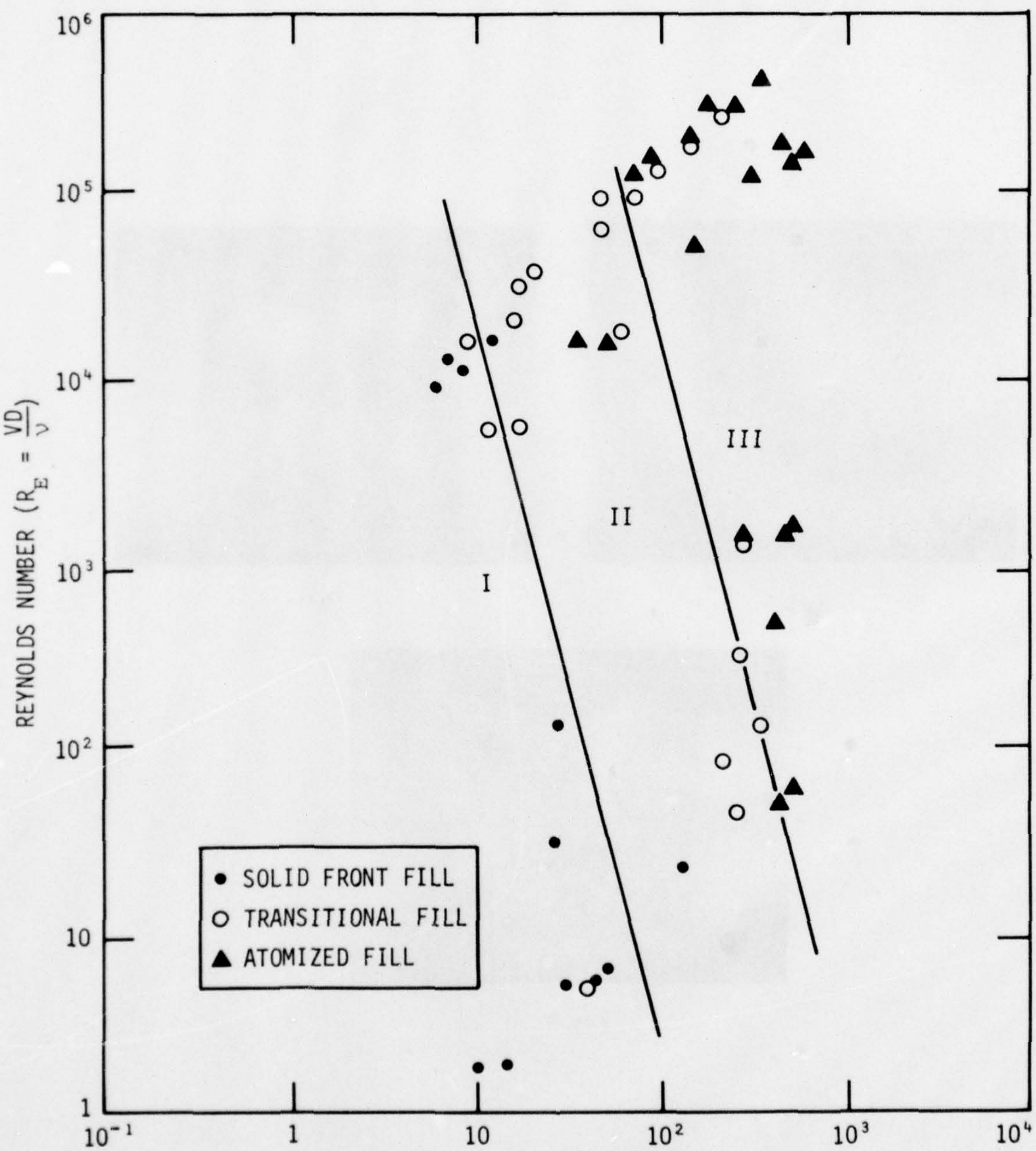
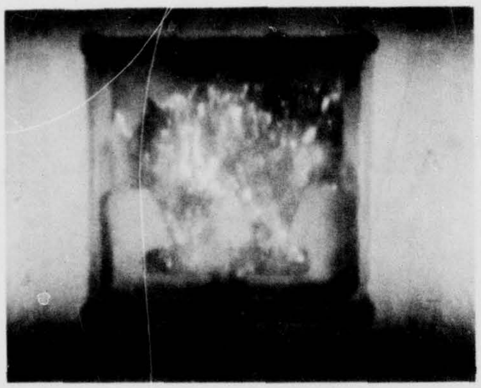


Figure 6. Experimental data obtained in the laboratory casting machine presented in terms of the Reynolds number versus the Weber number. This plot also permits prediction of the mode of die filling.



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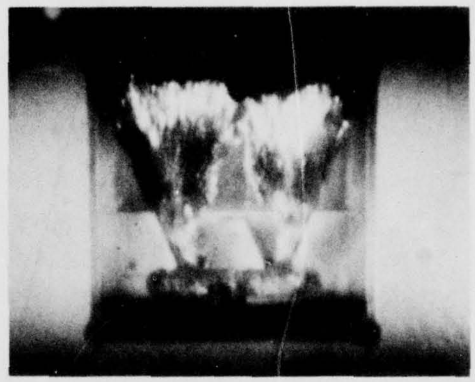

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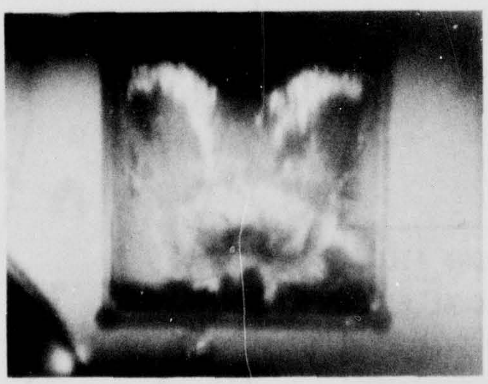
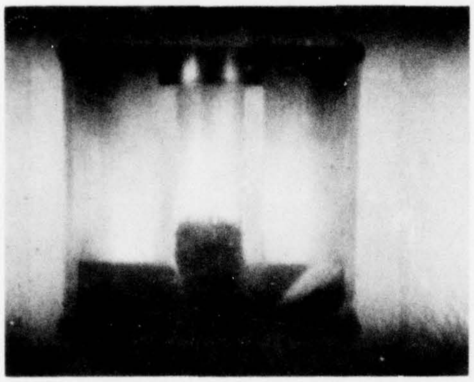


(c)

Figure 7. Photographs of the flow patterns observed during the casting of superheated Sn-15%Pb liquid alloy in the flat plate die cavity. (a) solid front fill at an ingate velocity of 5 feet per second; (b) transitional fill at an ingate velocity of 50 feet per second; and (c) atomized fill at an ingate velocity of 100 feet per second.



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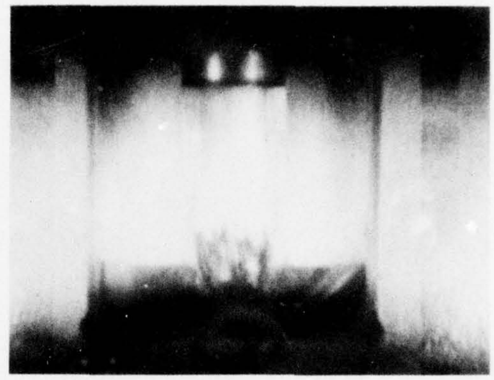

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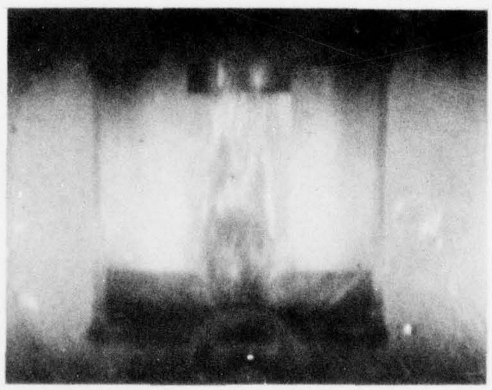

(c)

Figure 8. Photographs of the flow patterns observed during the casting of superheated Sn-15%Pb liquid alloy in the simulated turbine blade die cavity. (a) solid front fill at an ingate velocity of 5 feet per second; (b) transitional fill at an ingate velocity of 60 feet per second; and (c) atomized fill at an ingate velocity of 196 feet per second.

EXTENDING DIE LIFE

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SUMMARY

Thixocasting trials are described to optimize die life in steel castings, and to provide data for analysis of die heat flow behavior. Die materials studied have included H-13, H-21, operated warm, and "surface quenched" copper alloy dies operated at room temperature. Remarkable increases in life have been obtained with the copper die. Over 500 castings have been made thus far with no mold cracking or measurable dimensional change.

For most applications, the economics of die casting depend heavily upon the die amortization costs, basically the number of parts that can be made in a die before excessive cavity deterioration occurs. The die cavity serves two essential functions, firstly it must shape the cast metal to near net shape to minimize subsequent finishing operations and secondly it must be the sink to which heat from the cast metal flows in order to solidify. While many materials can adequately fulfill the first, shaping function, the latter is far less easy to satisfy.

As heat flows from the cast metal to the cavity it raises the adjacent cavity temperature creating thermal gradients and associated material expansions which are reversed on part ejection. Candidate die and machine component materials must be able to withstand this cyclic thermal shock which comes from repeated casting. They must also withstand the tendency to weld to the cast metal, plastically deform and chemically erode.

For zinc and aluminum alloys there are a variety of die steels such as H-11, H-13 which provide adequate service life, often in excess of 100,000 parts. For higher temperature alloys such as bronzes successful recourse has been made to more exotic materials such as Mo-TZM and tungsten based alloys or more sophisticated steel alloys such as the high tungsten H-21 steel.

For conventional ferrous alloy die casting, despite extensive university and industry research, no successful solution to the die material problem has been found. In fact, no alloys with melting temperatures much above 800°C are pressure die cast commercially in any quantity.

As alternative to the improvement of die materials, the Thixocasting process offers a radically new way to influence the character of the cast metal. Thus, for aluminum and bronze alloys for instance, Thixocasting at 50% solid offers substantial reductions in actual cast metal temperature.

For bronze alloy CDA 905 (used extensively as a model alloy in the Thixocasting development at M.I.T.) normal liquid casting would be at about 50°C superheat above the liquidus temperature or 1050°C. Thixocasting the same alloy can be accomplished at

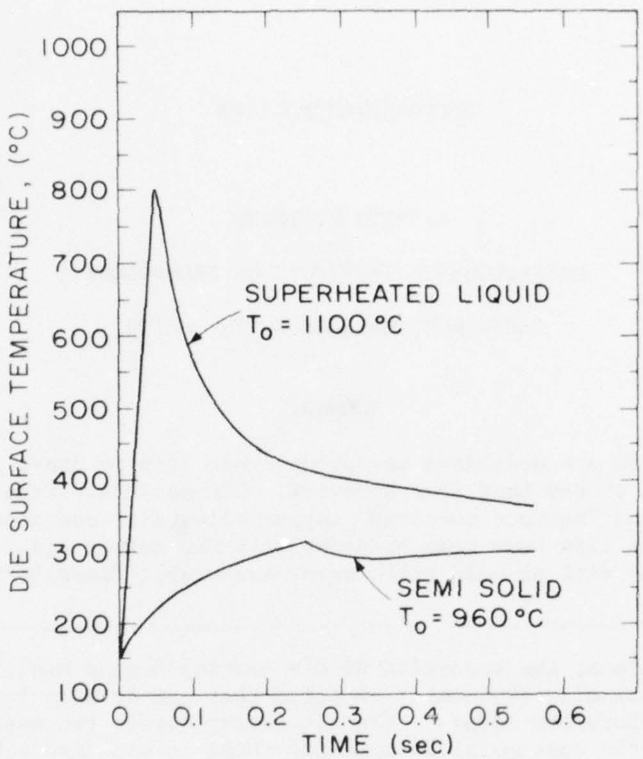


Figure 1: Computer extrapolation of die surface temperature variations based on experimental measurements 0.014" behind the die surface. Bronze alloy CDA 905 (88wt% Cu-10wt% Sn-2wt% Zn) cast into steel dies.

temperatures as low as 930°C. In this way high temperature bronzes such as this may be Thixocast at temperatures not significantly above those of conventionally liquid cast bronzes with melting points around 800°C.

The results of an experimental investigation (1) of these benefits can be seen in Figure 1. This shows die surface temperature variations with time predicted from a computer analysis of heat flow in the die and extrapolated from actual experimental measurements. Die surface thermal gradients, rates of temperature rise and maximum die temperatures were all found to be drastically reduced by Thixocasting. Furthermore, and far more significant for ferrous alloy Thixocasting, these results suggest that the rate of heat transfer across the mold/metal interface is also drastically reduced by Thixocasting.

With these encouraging results, an extended program to investigate die lives in Thixocasting stainless steel was initiated. This study was aimed at parts typically less than one pound. The study was split into two parts, 1) a series of controlled Thixocasting runs into a variety of die materials with periodic assessment of die wear and 2) a continuation of the analytical and experimental study of die heat flow behavior in Thixocasting.

One, immediate advantage to Thixocasting is the consistency of the charge prior to casting, Figure 2. This reduces the contact area between metal and shot chamber since the metal does not form a pool. Thus, both the extent of heating and tendencies for the shot chamber to warp are decreased.

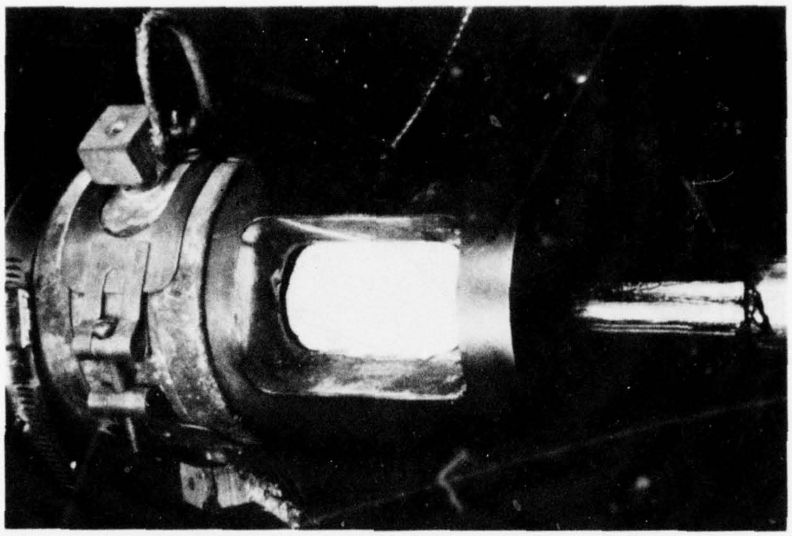


Figure 2: Reheated charge of AISI 440C about to be cast.

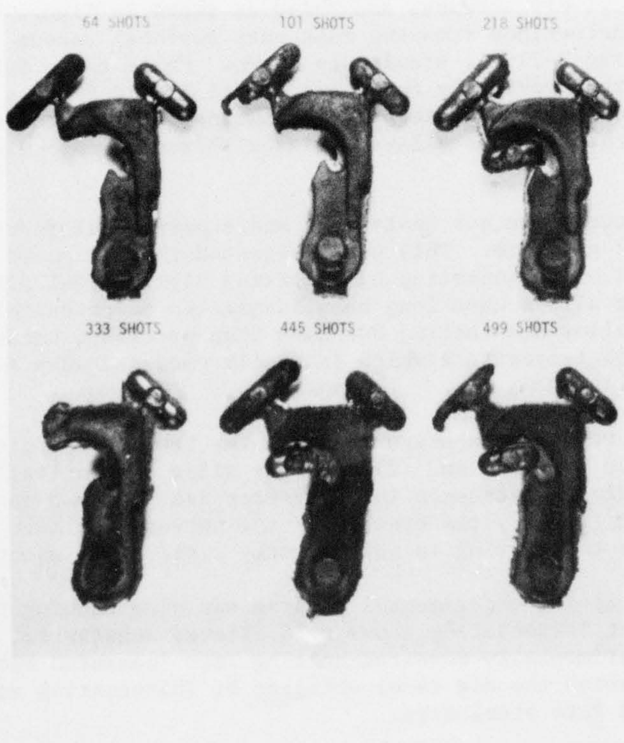


Figure 3: Sequence of Thixocast parts. AISI 304 stainless steel cast into H-13 steel dies.

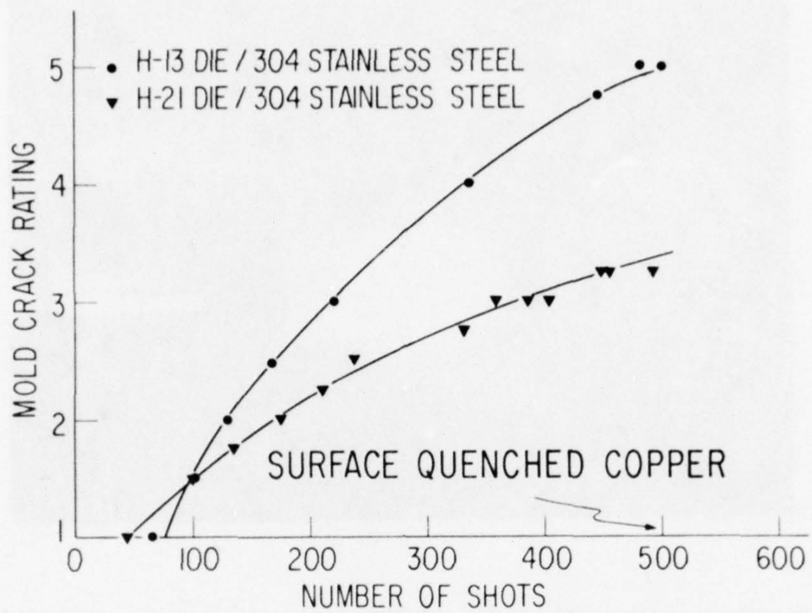


Figure 4: Mold crack rating versus number of shots. Thixocast AISI 304 stainless steel.

A typical series of Thixocast AISI 304 stainless steel parts is shown in Figure 3. These parts were subjectively assessed and rated as shown in Figure 4. This is a graph of mold crack rating (determined from the cast part surface) versus the number of shots. Results for both H-13 and H-21 die steels are shown. While these data are significantly better than that reported previously for conventional liquid ferrous die casting, they were not what we believed was possible by Thixocasting. In the course of this work however it was confirmed that ferrous alloys could be Thixocast into dies at or near room temperature.

At this stage we turned to our analytical and experimental investigations of heat transfer in the die for guidance. This work suggested that we could exploit the die filling characteristics of Thixocasting by utilizing high thermal diffusivity die materials such as copper. Copper alloys have long been identified as potential die materials for high pressure ferrous alloy die casting but have been precluded because of their relatively low softening temperature which is easily exceeded when conventional liquid practices are observed.

Figure 5 shows a computed comparison between the temperature/distance profiles in 1) a steel die preheated to 300°C and 2) a copper alloy die initially at 40°C. It can be seen that the maximum die temperatures in the copper die do not exceed 300°C. Note that the same amount of heat (roughly the area under the curves) has been absorbed by the die in each case, such that the casting is sufficiently rigid to be ejected.

Furthermore, our ongoing experimental program was also showing that increasing the volume fraction solid at Thixocasting above 0.50 offered substantial benefits. Thus Figure 6 shows the experimentally measured heating rate (measured with fine chromel/alumel thermocouples 0.014" behind the die face) obtained by Thixocasting stainless steel at various fractions solid into steel dies.

The experimental approach that we adopted at this stage was therefore 1) increase the fraction solid at casting, 2) employ copper alloy dies at room temperature, 3) minimize mold/metal contact time by ejecting parts with minimum delay, 4) rapidly return

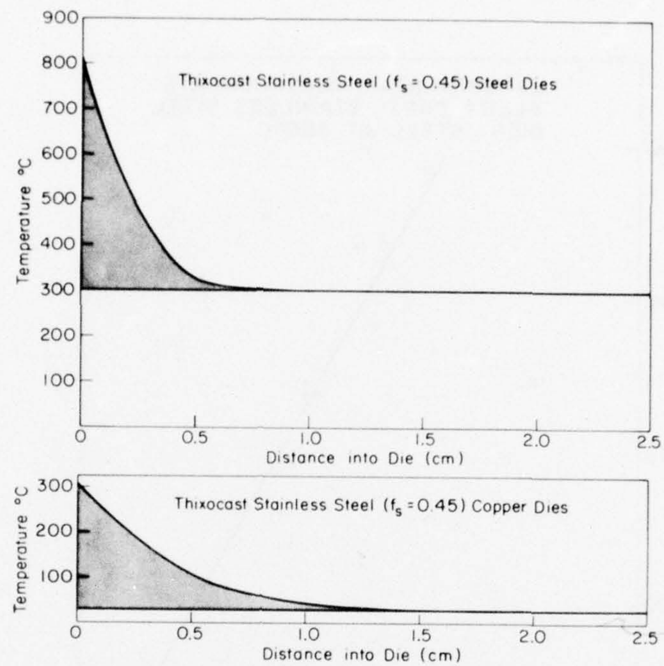


Figure 5: Computed comparison of temperature distance profiles for 1) steel dies preheated to 200°C and 2) copper alloy dies at 40°C. Similar amounts of casting solidification have occurred.

the dies to room temperature and eliminate heat penetration by <u>surface quenching</u> the dies with water immediately after ejection.

The first copper alloy we examined was a casting alloy Cu-0.8 Cr hardened to R_B 70 which has a thermal diffusivity roughly ten times that of H-13 steel. A comparison of the 500th part cast into that and the H-13 and H-21 dies is shown in Figure 7 (fraction solid for all these trials was held at 0.50). No mold cracking was detected as is also shown in Figure 4. Subsequent work has been on a Cu-0.5 Cr-0.5 Zr alloy and casting volume fraction has been increased to 0.65. Slightly higher pressures (10,000 psi) than in the lower fraction solid casting (6,800 psi) have been employed and to date 650 castings have been made without significant mold cracking. Typical metal residence times in the cavity in these trials was 0.2 seconds but this was sufficient to fully solidify the castings and allow ejection without part damage.

Many more castings will now be made to fully confirm the value of the Surface Quenched Copper dies. However, based on these experiments to date, extrapolation of the current data suggest that this is the breakthrough required to permit large volume ferrous alloy Thixocasting. Furthermore, surface quenched copper dies offer several additional benefits. Firstly, the copper chromium alloy is a casting alloy which should therefore permit cast die preforms and thus radically reduce die costs (as is now emerging as a viable route for some steel alloys dies). Secondly, the dies operate at room temperature and thus will speed maintenance by eliminating both cool down and preheat time. Thirdly the adoption of surface cooling instead of water lines running through complicated internal passages eliminates much of the cost of die building and installation.

REFERENCES

1. D. G. Backman, R. Mehrabian, M. C. Flemings, "Die Thermal Behavior in Machine Casting of

Partially Solid High Temperature Alloys", presented to 105th AIME Meeting, Las Vegas, 1976.

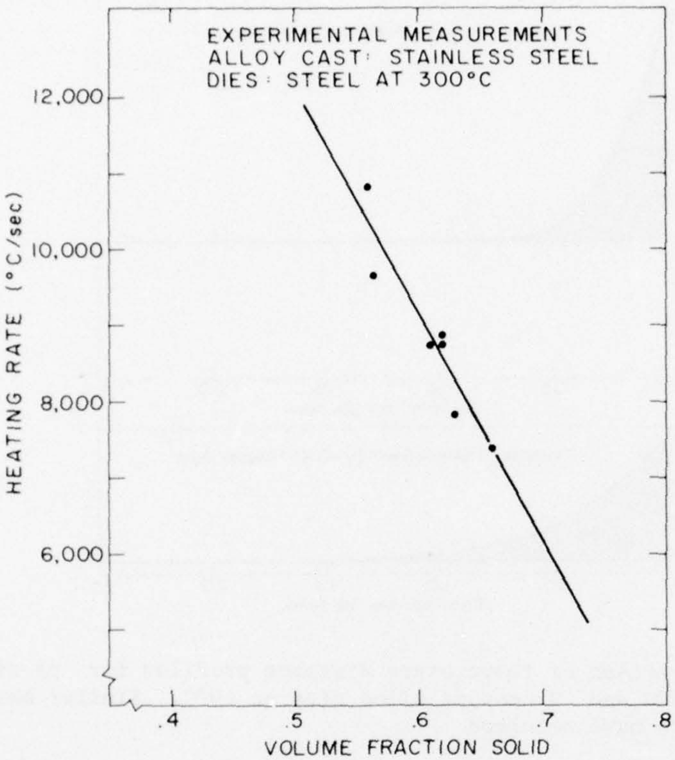
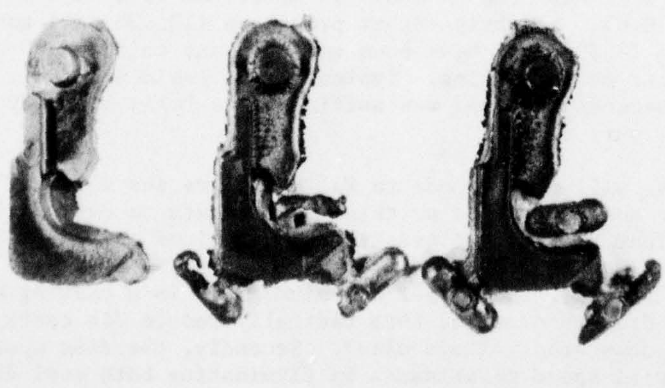


Figure 6: Experimentally measured heating rate taken from thermocouples located 0.014" behind the steel die surface versus volume fraction solid at Thixocasting (from Bond).



(a) (b) (c)

Figure 7: 500th Thixocasting from a) H-13 steel die, b) H-21 steel die, c) Surface Quenched Copper die.

THIXOFORGING: PRELIMINARY STUDIES

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A laboratory apparatus is described that permits production of components from partially solid, Rheocast, charge materials in a forging type operation. It consists of a reheat furnace, a penetrometer and a hydraulic press containing controlled temperature dies. Rheocast ingots of low temperature model Sn-15%Pb alloy and aluminum alloys 6061 and Al-4.5%Cu were reheated to predetermined volume fractions solid in their liquid-solid temperature range and pressed into shape. Even with the severe limitations of the present hydraulic press the parts produced had acceptable surface finish and internal soundness. Thixoforged 6061 aluminum parts in the T6 heat treated condition had tensile properties: Y.S. ≈ 25 Ksi, U.T.S. = 36.5 Ksi, Elong. ≈ 18.5%.

I. INTRODUCTION

Current emphasis on reduction of manufacturing costs by the government and industry has resulted in renewed efforts to develop new and innovative processes that would permit direct forming of metal parts to net or near net shapes. This paper reviews recent work at the University of Illinois directed toward the production of components by forging type operations exploiting the special metallurgical structure and rheological behavior of Rheocast alloys. Specifically, Rheocast ingots were produced using continuous apparatuses. These ingots were subsequently reheated to their liquid-solid temperature range, placed between two die halves and pressed into shape. The process is similar to squeeze casting except the charge material is partially solid and thixotropic.

Work to date, summarized in this paper, has been carried out in the following areas:

1. A small laboratory apparatus was built which is suitable for experiments with Sn-Pb and aluminum alloys.

2. Experiments have been carried out with both completely liquid and partially solid slurries of the two alloy systems.

3. Mechanical properties of 6061 aluminum alloy parts produced have been determined.

II. APPARATUS AND PROCEDURE

The laboratory apparatus for forging of reheated Rheocast ingots into shapes is shown in Figure 1. It consists of (a) a resistance heated furnace, (b) a controlled pressure penetrometer to determine whether the previously Rheocast charge material has reached the correct consistency (volume fraction solid) for the forging operation, and (c) a 50 ton Wabash hydraulic press containing a controlled temperature die set. A detailed description

of the apparatus, process variables and operating procedure are given below.

The resistance furnace for reheating previously Rheocast slugs (∿1 1/2" in diameter by ∿2" long) is shown on the left side of Figure 1(a). Its temperature is automatically controlled. The penetrometer located above the resistance furnace consists of a 1/8" diameter alumina rod attached at one end to a small air cylinder. The lower end of the penetrometer rests on top of the Rheocast slug and exerts a controlled amount of pressure on the slug. The slug is reheated to its liquid plus solid temperature range. When it reaches the desired volume fraction of solid it becomes soft enough for the rod to penetrate the slug. The two variables in this operation are the pressure exerted by the alumina rod on the slug and the rate of penetration. For each alloy system studied thermocouples were located in the slugs and a number of experiments were carried out to determine (1) the furnace power settings for uniform heating of the slug, and (2) the pressure necessary to penetrate a slug of a given volume fraction solid. In subsequent experiments, once a charge material reached the desired volume fraction of solid it was transferred to the lower die half in the hydraulic press for the forging operation.

The set of H-13 dies shown in Figure 1(b) and Figure 2 were provided by the Doehler Jarvis Division of National Lead Industries. A set of die holders were built to adapt the die-set to the hydraulic press. Resistance heaters and thermocouples were located in the two die halves. Die temperature was automatically controlled. A set of three thermocouples located at varying distances from the metal-die interface were placed in the ejector to measure thermal profiles in the die.

During operation, the reheated slug of Rheocast metal was placed in the lower die half, the dies were closed forcing the slurry upward to form the cup-shaped part, Figure 2. For comparison, experiments were also carried out with completely liquid charge material. The die closing velocity and pressure were preset prior to each forming cycle. Maximum pressure available was ∿50 tons. A photograph of the parts produced is shown in Figure 1(b).

Successful operation of this process requires an understanding of the effect of process variables on heat flow, metal flow and solidification. The process variables are:

(a) Alloy composition
(b) Temperature and volume fraction solid of the charge
(c) Die material
(d) Die temperature
(e) Die Coating
(f) Shear rate - press speed
(g) Time and magnitude of applied pressure
(h) Time under pressure.

III. STRUCTURE AND PROPERTIES OF PARTS PRODUCED

The three alloys used in these preliminary studies were: low temperature model Sn-15%Pb alloy and aluminum alloys 6061 and Al-4.5%Cu. Experiments were carried out with both liquid and Rheocast charge materials.

Figure 3 shows photographs and the microstructure of Thixoforged Sn-15%Pb alloy parts. The volume fraction of solid in the initial charge was ∿0.5. The larger spheroidal particles in Figure 3(b) were those existing in the charge prior to pressurization. The darker matrix is the eutectic liquid that solidified last. Die temperature and applied pressure for successful production of Sn-15%Pb alloy parts were ∿150°C and 20 tons, respectively. Maximum die closing speed was limited by the hydraulic press used. It was 2 cm/sec.

Figure 4 shows a photograph and the microstructure of an Al-4.5%Cu part. Volume fraction solid in the initial charge was ∿0.4. Die temperature and final pressure were

$\sim$450°C and 20 tons, respectively. The microstructures of 6061 aluminum alloy parts produced with a Rheocast and a completely liquid charge material are shown in Figure 5. The Thixoforged part had an initial volume fraction solid of $\sim$0.65. In experiments with the higher temperature aluminum alloys, relatively high die temperatures, 400 to 500°C, were necessary for production of parts with good surface finish and internal microstructures. This was necessitated by the speed limitations of the hydraulic press used. Cooler dies resulted in further solidification of the charge material before the two die halves came together. Under these conditions parts could not be completely filled and contained sheets of internal oxides.

Parts made from both liquid and Rheocast charge of 6061 aluminum alloy were sectioned, heat treated to T6 condition and tested for tensile properties. Average tensile data from several specimens are listed in Table I. Results to date show that even with the limitations of the present apparatus, Thixoforgings made can be heat treated, and possess relatively good tensile properties.

Work to date has shown that a more versatile hydraulic power supply with controlled faster speeds as well as controlled applied pressure will be necessary for successful Thixoforging of higher temperature alloys. Future experiments with steels and superalloys will be carried out with (1) an induction powered slug reheating furnace and (2) a modified MTS hydraulic power supply and associated controls for the forging cycle of the operation. Finally, studies are presently underway to develop a predictive model of heat flow during solidification of the parts. Measured thermal profiles in the castings and the dies are being compared with theoretical heat flow models to permit determination of heat transfer coefficients before and after pressurization.

ACKNOWLEDGEMENT

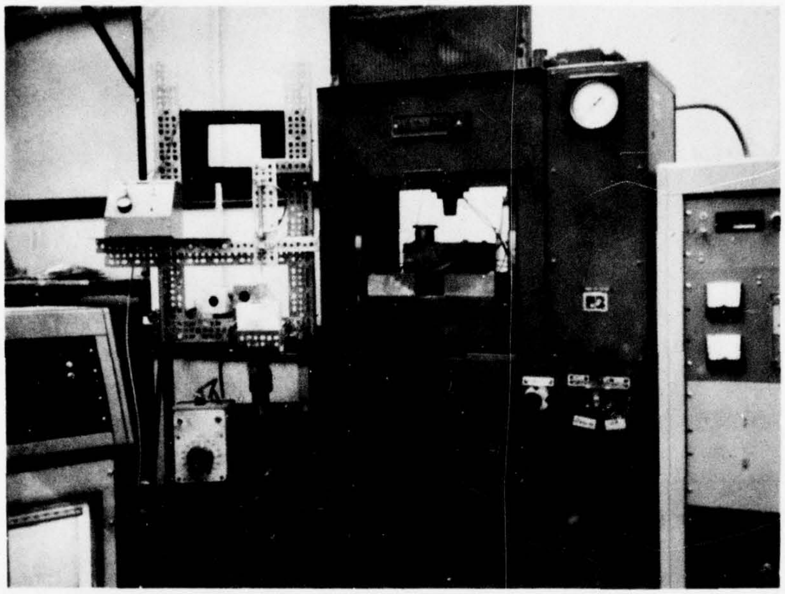
The work reported is being sponsored by the Army Materials and Mechanics Research Center, Watertown, Mass. The authors are indebted to Dr. G. Kotler of Doehler-Jarvis Division of NL Industries, Inc. for the dies used in this investigation.

TABLE I

Tensile Properties of 6061 Aluminum Alloy Parts Heat Treated to T-6 Condition

Die Pressures were 30 Tons

	Y.S.(Ksi)	U.T.S.(Ksi)	% Elong. in 1/2" Section
Rheocast Ingot	24	30	4
Thixoforged Die Temp. 450°C	22	31	7
Thixoforged Die Temp. 500°C	25	36.5	18.5
Squeeze Cast	29	36.5	9



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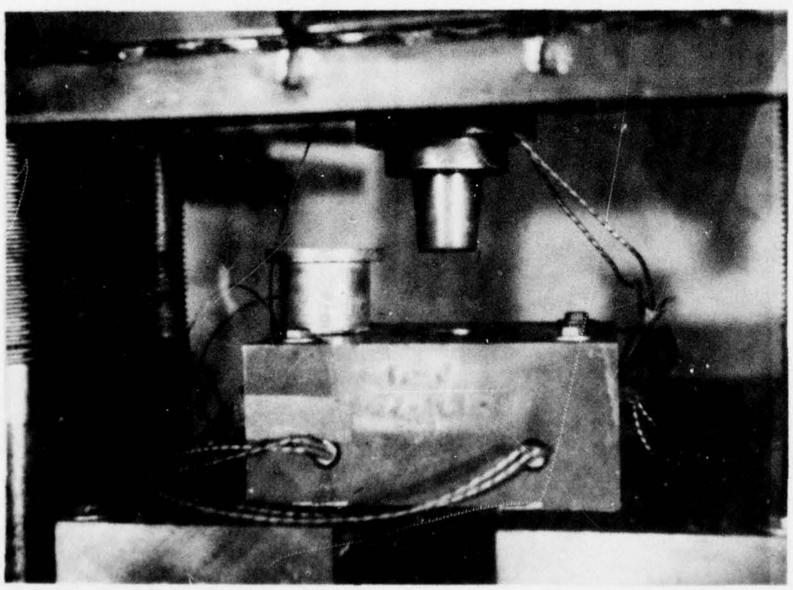


(b)

Figure 1. Photographs of apparatus for Thixoforging of partially solidified alloys into shapes. (a) shows an overall view of the apparatus including slug reheating furnace, penetrometer, hydraulic press and controllers. (b) shows the two die halves and the part produced.

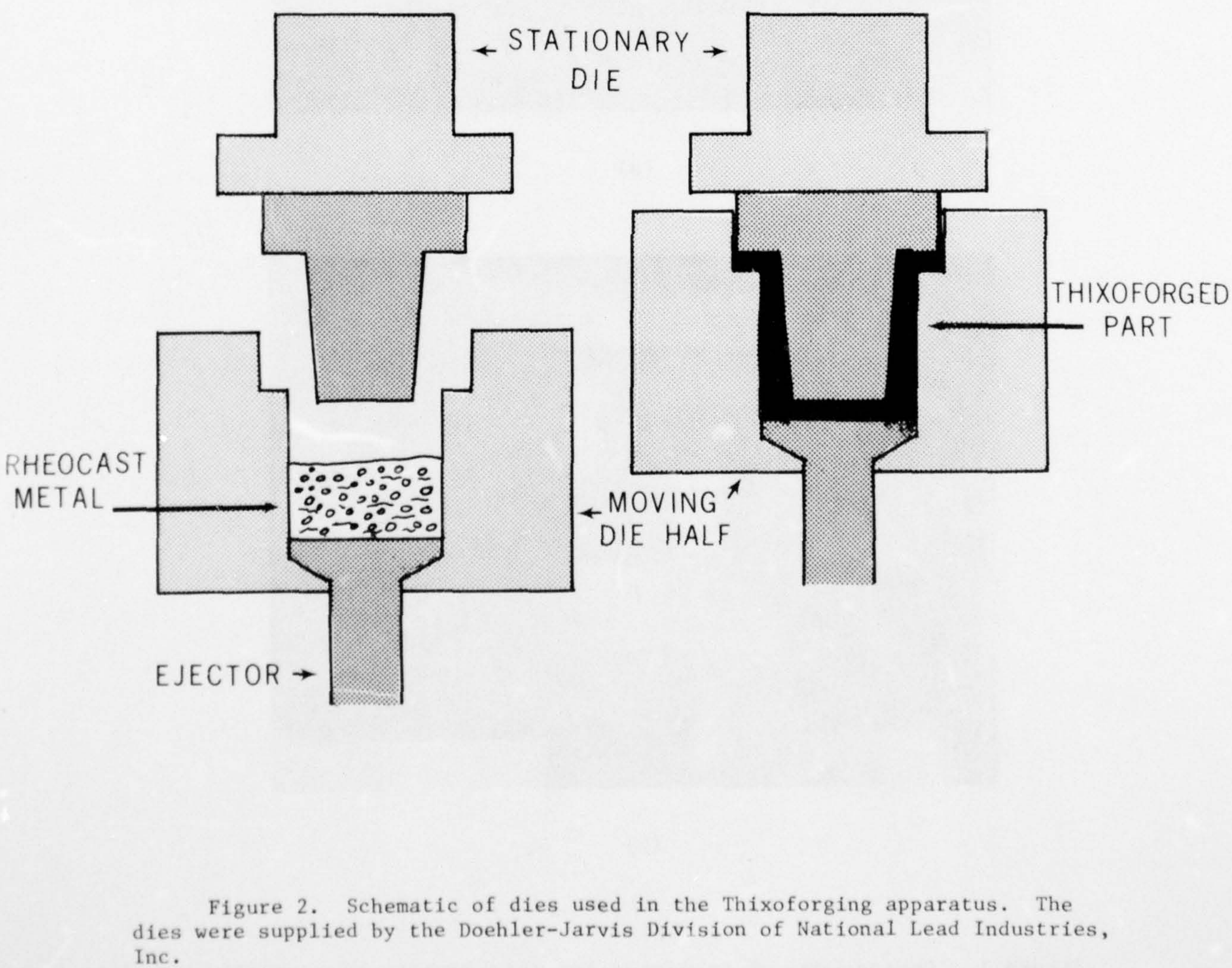
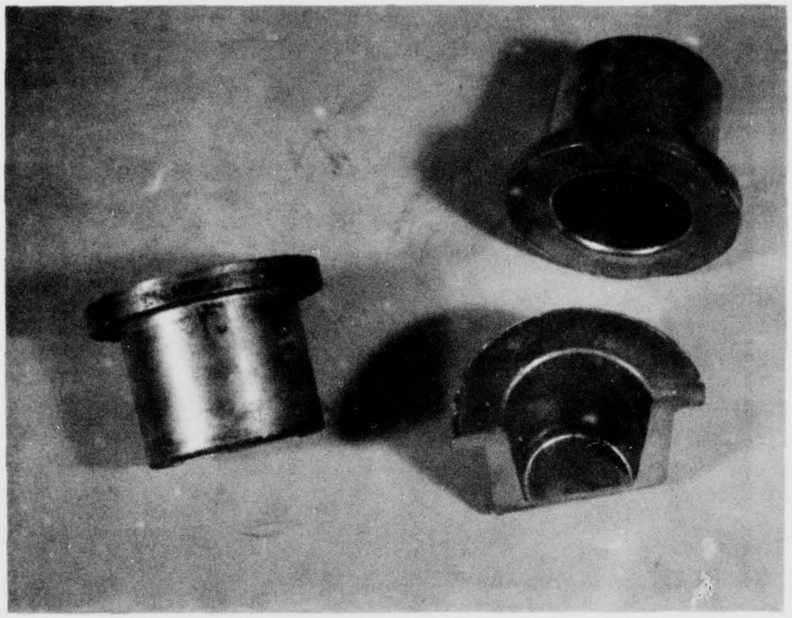


Figure 2. Schematic of dies used in the Thixoforging apparatus. The dies were supplied by the Doehler-Jarvis Division of National Lead Industries, Inc.



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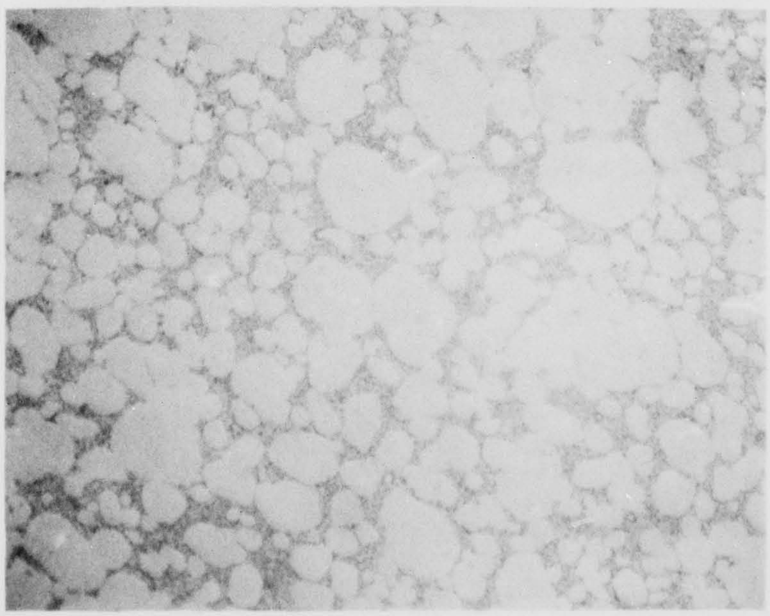
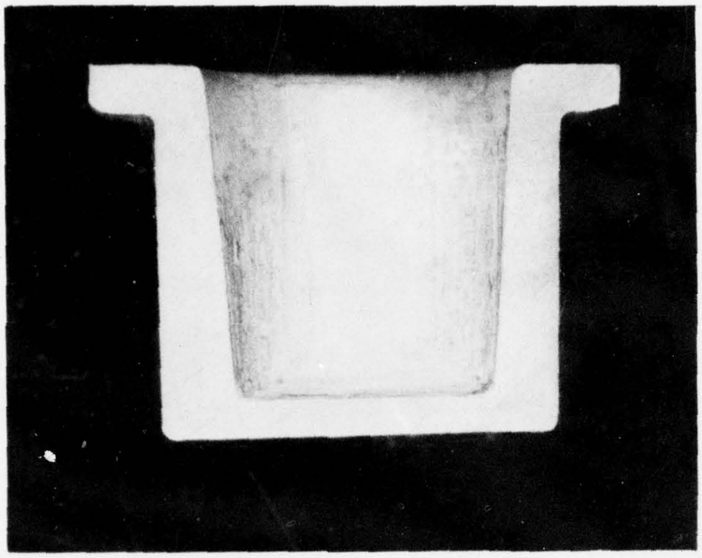
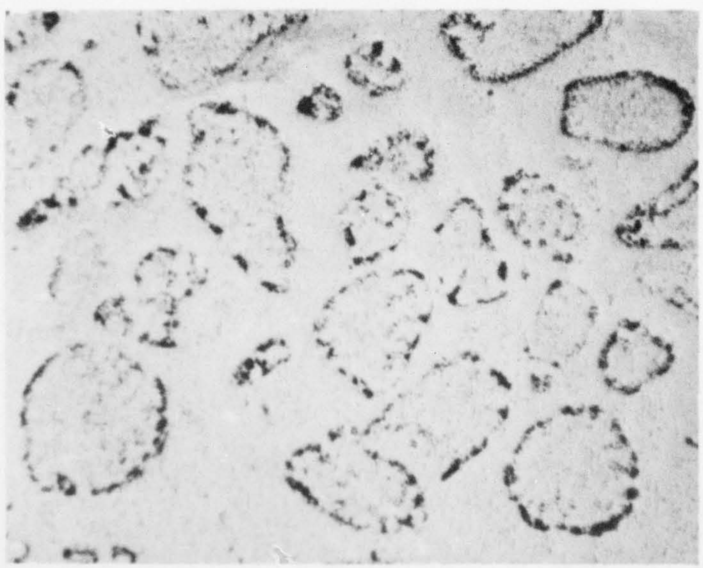


(b)

Figure 3. Photograph and microstructure of a Sn-15%Pb cup shaped part made in the Thixoforging apparatus when the initial charge material was ~50% solid. (a) shows photographs of two complete parts and a longitudinally sectioned part. (b) shows the internal microstructure of the part at 100X.

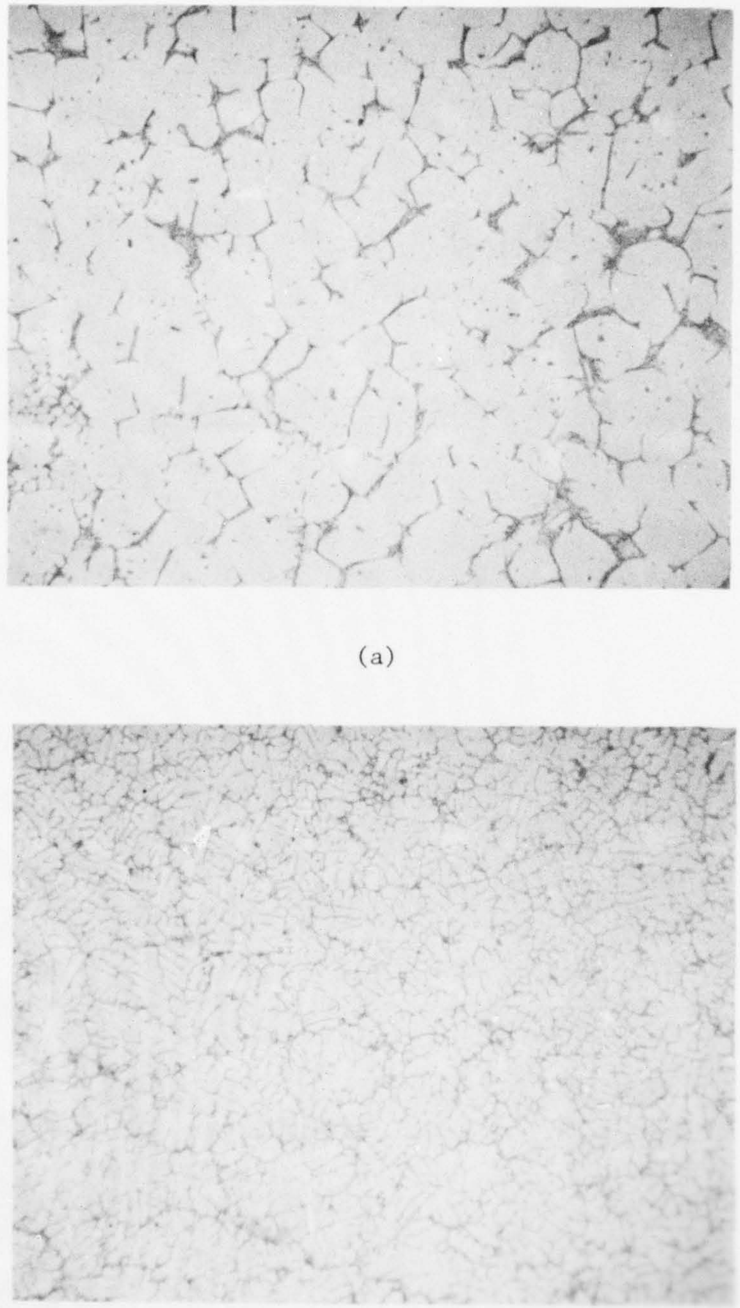


(a)



(b)

Figure 4. Photograph and microstructure of Thixoforged Al-4.5%Cu alloy part. (a) Photograph of a longitudinally sectioned part; (b) internal microstructure of the part at 75X.



(a)

(b)

Figure 5. Microstructures of 6061 aluminum alloy parts at [illegible]
(a) Thixoforged part at volume fraction solid of [illegible]; (b) part made [illegible]
completely liquid initial charge.

STRUCTURE, HEAT TREATMENT AND PROPERTIES OF RHEOCAST ALLOYS

by

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ABSTRACT

Rheocast water quenched specimens and ingots of 905 copper base alloy, 440C stainless steel and X-40 cobalt base superalloy were produced continuously in a high temperature Rheocasting machine. These were subjected to various homogenization heat treatments and their mechanical properties were determined. Electron microprobe analysis of water quenched specimens consistently showed flat elemental composition profiles of alloying elements in the primary solid particles with abrupt changes at their boundaries. However, homogenization heat treatment of both 440C stainless steel and X-40 cobalt base superalloy eliminated the Rheocast duplex structure resulting in significant redistribution of solute elements and some alteration of the carbide morphology and distribution. The Rheocast ingots in the absence of porosity possess mechanical properties comparable to material produced by conventional casting.

I. INTRODUCTION

In general, engineering alloys freeze over a range of temperatures and liquid concentrations. As a consequence, the different elements that are combined to make up an alloy segregate during solidification. Short range segregation (microsegregation) occurs on the dendritic scale in conventional castings. One may thus anticipate a similar segregation phenomenon in Rheocast metals. Microsegregation spacings in Rheocast metals would be on the scale of the primary solid particles when the slurry is slowly solidified in a mold resulting in an essentially equiaxed structure. On the other hand, if the slurry is rapidly solidified, as in die casting, the remaining liquid solidifies in a dendritic mode and a duplex microstructure is obtained -- the primary solid particles are surrounded by a fine dendritic network. The important influence of dendrite arm spacings on the mechanical properties of conventional castings, and of wrought material produced from conventionally cast ingots, is well documented. Large improvements in mechanical properties can also result from high temperature "homogenization" treatments. Whether the time necessary to obtain significant homogeneity is short enough to be commercially feasible depends on the spacings over which concentration differences occur. As noted in another paper in this volume (1), both dendrite arm spacings in conventional castings and primary solid particle size in Rheocast slurries decrease with increasing average cooling rate during solidification. Thus, one would expect that, regardless of differences in microsegregation profiles between dendritic and Rheocast alloys, the finest primary solid particle size should give the shortest response to "homogenization" heat treatment.

Application of Rheocast technology to specific commercial forming and casting processes would be realized once the full range of static and dynamic properties of a number of Rheocast alloys are documented. In the past year a comprehensive study was initiated

at the University of Illinois to determine the effect of cast (Rheocast) structure on microsegregation, homogenization heat treatment response and mechanical properties of several high temperature alloys. Preliminary results from this work are presented below. It should be noted that the measured properties reported were obtained from static ingots cast using the high temperature continuous Rheocasting machine previously described (1).

II. STRUCTURE OF RHEOCAST ALLOYS

The three alloys studied were 905 copper base alloy (Cu-10%Sn-2%Zn), 440C stainless steel (Fe-17%Cr-1%Mn-1%Si-0.6%C) and X-40 cobalt base superalloy (Co-26.5%Cr-10.5%Ni-7%W-0.5%C). Typical Rheocast (water quenched) structures of two of the alloys are shown in Figure 1. For comparison, Figure 1 also shows the corresponding conventionally solidified dendritic structures of the alloys. As previously noted (1) the primary solid particle size in the Rheocast alloys is primarily a function of average cooling rate during solidification. Therefore, processing techniques that can increase cooling rate during continuous Rheocasting and yet permit solidification of spheroidal primary solid particles could become of foremost importance in the future. The structure of Rheocast ingots of the 440C stainless steel and the X-40 cobalt base superalloy are shown in Figure 2. Due to the slower cooling rates achieved in the insulated molds (1¼" in diameter by 7" high) the ingots do not show the typical duplex structure of the water quenched slurries. The primary solid particles coarsen during solidification in the ingot molds.

III. MICROSEGREGATION, HEAT TREATMENT RESPONSE AND PROPERTIES

Ingots of the three alloys were subjected to different homogenization heat treatments and their mechanical properties were determined. Electron microprobe analysis of water quenched slurries consistently showed flat elemental composition profiles of alloying elements in the primary solid particles with abrupt changes at their boundaries. An example of this observation in the X-40 cobalt base superalloy is shown in Figure 3. This segregation profile differs from conventional dendritic microsegregation where a minimum concentration gradient is usually observed at the center of dendrite arms. The flat profiles are probably due to increased time available for diffusion in the solid during slow primary solidification. Homogenization heat treatment of the specimen at 1300°C for 5 hours in a vacuum of 6×10^{-5}mm of Hg eliminated the Rheocast duplex structure resulting in significant redistribution of solute elements coupled with some dissolution, transformation and redistribution, and coarsening of the carbides, Figure 4. Typically, the conventional cast microstructure of X-40 cobalt base alloy (also known as H.S. 31) consists of solid solution matrix (γ) present in the form of cored dendrites surrounded by islands of carbide networks. The coring is a result of chemical partitioning of nickel, chromium and tungsten in cobalt. The principle carbide phase in this alloy is of the $M_{23}C_6$ type where chromium and tungsten participate predominantly in the carbide formation (2). Other carbide morphologies such as M_7C_3 and M_6C have also reported in this alloy family (3). Detailed microhardness measurements were carried out across the primary solid particles of as-Rheocast and heat treated specimens using a 25 gram load, Figure 5. The carbide/primary solid particle interface has been denoted as the edge of the grain and the KHN is normalized by taking the ratio of hardness at a given location to the minimum value which consistently occurred at the center of the primary solid particles. In the as-Rheocast condition the microhardness inside the primary solid particles exhibited no change complementing the microprobe analysis of Figure 3. Heat treatment for five hours at 1100°C and 1300°C increased the relative hardness in the particles significantly, Figure 5. Dissolution of grain boundary carbides, solute redistribution, and reprecipitation of fine carbides during furnace cooling after heat treatment are responsible for the changes in relative microhardness.

Mechanical properties of the three alloys were measured in the as-Rheocast and heat treated conditions. Room temperature tensile properties of the 905 copper base alloy are listed in Table I. The properties obtained are comparable to conventional dendritically

solidified castings. Rheocast ingots of 440C stainless steel were homogenized at 1100°C to 1300°C for times of up to 20 hours. Compression test specimens from these ingots were subjected to standard 440C alloy quench and temper heat treatment. The specimens were tested at different temperatures up to 600°C. It was found that 0.2 percent offset yield strength improved with increasing time and temperature of homogenization heat treatment, Figure 6. For example, the room temperature yield strength of the as-Rheocast material was approximately 150 KSI. After five hours at 1300°C, the measured yield strength increased to approximately 240 KSI. This value is close to the 270 KSI reported for wrought 440C. Improvement in the yield strength of the as-Rheocast alloy with homogenization heat treatment is a direct consequence of transformation of the grain boundary M_7C_3 carbides to $M_{23}C_6$ carbides. This conversion is accompanied by the diffusion of carbon and homogeneous redistribution of the latter carbides within the equiaxed grains of the alloy (4).

Heat treatment of the Rheocast ingots of the X-40 cobalt base superalloy at 1100°C and aging for 50 hours at 700°C affected the mechanical properties in a different way, Figure 7. This heat treatment resulted in coarsening of the carbides as well as changes in their chemistry. The coarsened carbides reduce the yield strength of the Rheocast alloy. For comparison, dendritic ingots of the alloy were cast at equivalent cooling rates. The compressive yield strengths of the dendritic specimens are comparable to that of the Rheocast ingots, Figure 7.

Tensile and stress rupture properties of Rheocast ingots of X-40 cobalt base superalloy are compared to reported conventional investment cast properties of the alloy in Table II. While the yield strengths are equivalent, the ductility and ultimate yield strength of the Rheocast ingots are lower. Metallographic examination showed that the lower ductilities are due to extensive microporosity in the Rheocast ingots. The high volume fraction of the slurry and lack of directional solidification were responsible for the observed microporosity. The ingots were hot isostatically pressed to eliminate the porosity prior to stress rupture testing. As noted in Table II the stress rupture properties of the Rheocast ingots are comparable to investment casting and exceed the minimum design requirements in aircraft components.

The results reported above show that Rheocast ingots respond to heat treatment and in the absence of porosity possess mechanical properties comparable to conventional casting. Therefore, as in conventional processes, variables during Rheocasting and subsequent casting or forming operations should be closely controlled to obtain sound components. Finally, it should be noted that these are preliminary results and further studies are necessary to establish optimum heat treatment conditions for a given Rheocast alloy.

ACKNOWLEDGEMENT

The work reported here was sponsored by Advanced Research Projects Agency, Arlington, Virginia. It was monitored by Army Materials and Mechanics Research Center, Watertown, Massachusetts. Stress rupture tests were done by the Casting Development Section of Pratt and Whitney Aircraft in Manchester, Connecticut.

REFERENCES

1. S.D.E. Ramati, D.G. Backman, Y.V. Murty, G.J. Abbaschian and R. Mehrabian, "FUNDAMENTAL ASPECTS OF RHEOCASTING," in this volume.

2. C.T. Sims and W.C. Hagel, Super Alloys, John Wiley & Sons, New York, p. 145-174 (1972).

3. F.R. Morral, L. Habraken, D. Coustsouradis, J.M. Drapier and M. Vrbaian: Metals Engineering Quarterly, Vol. 2, p. 1-16 (May 1969).

4. J.M. Oblak and W.H. Rand, "Structure and Properties of the Rheocast Ferrous Alloy 440C," Metallurgical Transactions B, v. 7B, p. 705 (1976).

5. Standard Handbook, Cast Copper and Copper Alloy Products, Copper Development Association, Inc., N.Y., p. 106 (1970).

TABLE I

Mechanical Properties of Copper Base Alloy 905

	YS (KSI)	UTS (KSI)	% Elongation
As Rheocast	19	47	30
Rheocast and Homogenized at 770°C for 20 hours	22.6	44.3	23
Conventional Dendritic Alloy*	22	45	25

*Typical mechanical properties of commercial conventionally cast 905 alloy reported in Reference 5.

TABLE II

Mechanical Properties of X-40 Cobalt Base Alloy

Property	As-Rheocast	Investment Cast	Design Minimum
0.2% Tensile Yield Strength (KSI)	77	76	50
Ultimate Tensile Strength (KSI)	96	108	83
% Elongation	3.0	7	4.0
Stress-Rupture at 790°C and 30 KSI following isostatic pressing at 2215°F and 15,000 psi	58.6	60	--

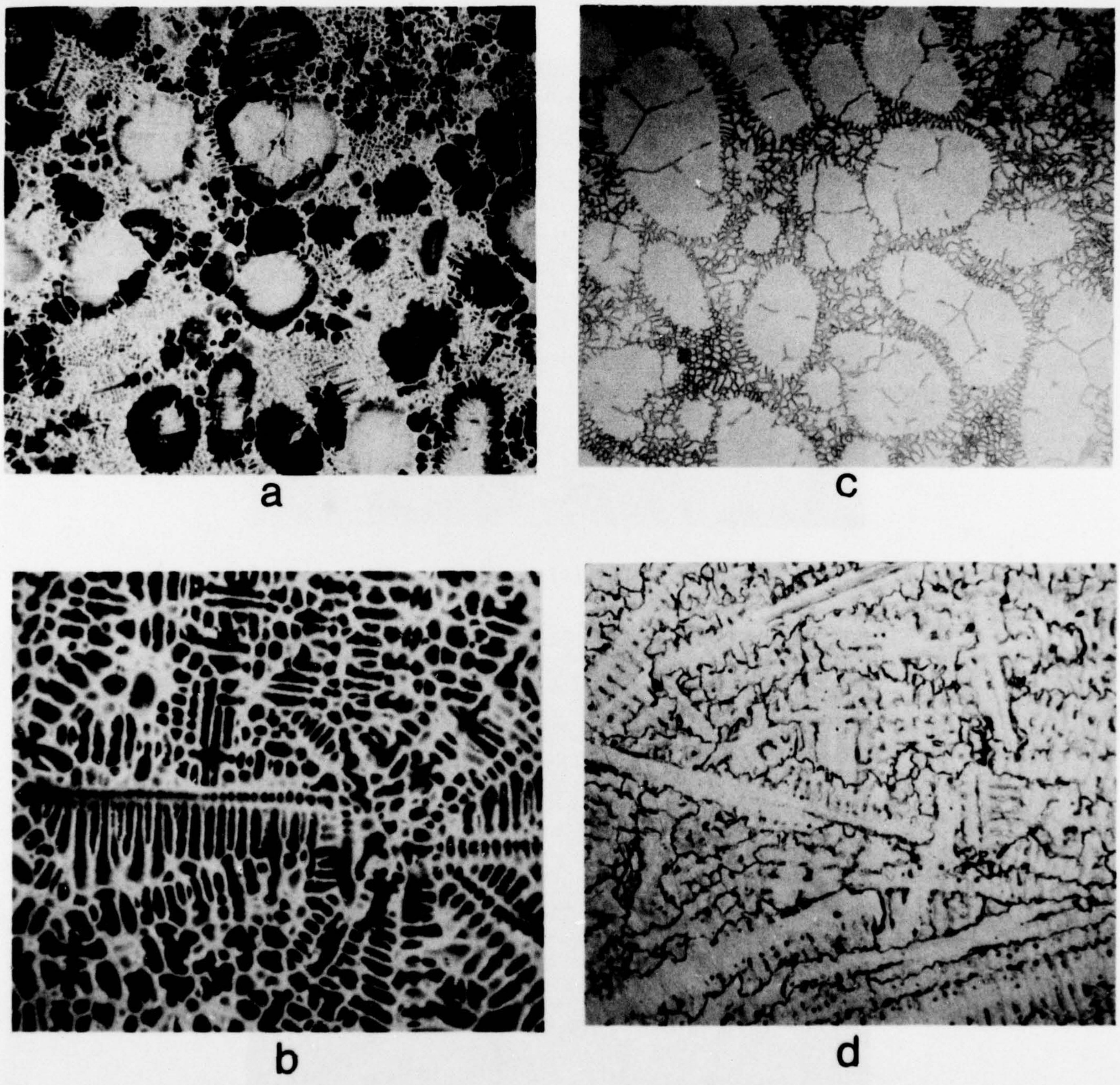
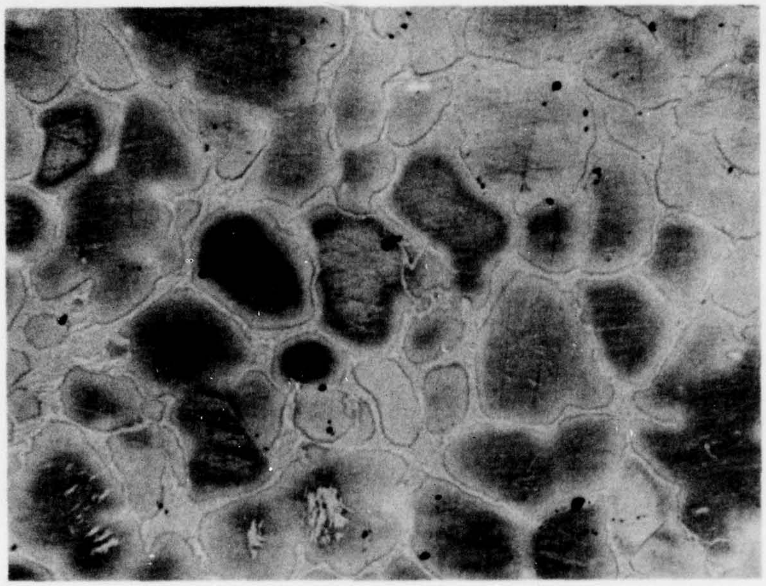
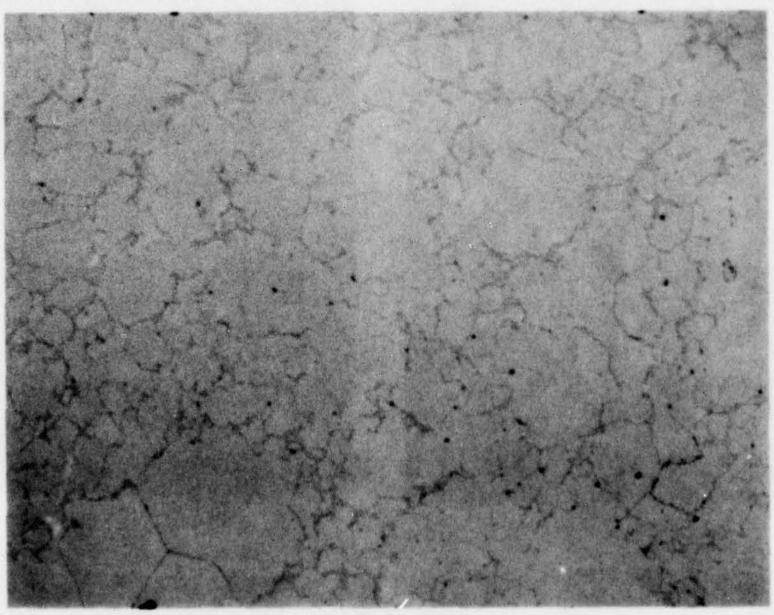


Figure 1. Comparison of Rheocast and conventionally cast (dendritic) microstructures of high temperature alloys solidified at equivalent cooling rates; (a) and (b) show the Rheocast and conventional dendritic microstructures of 440C stainless steel, respectively; (c) and (d) show the Rheocast and conventional dendritic microstructures of X-40 cobalt base superalloy, respectively. Magnification 100X.



(a)



(b)

Figure 2. Ingot microstructures of continuously produced semi-solid alloy; (a) 440C stainless steel and (b) X-40 cobalt base superalloy. Samples were slowly cooled in ingot molds. Magnification 100X.

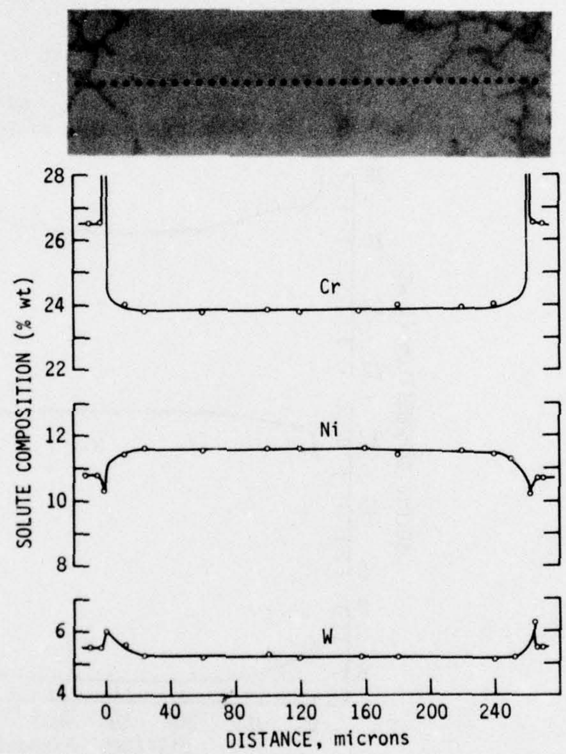


Figure 3. Composite figure showing microprobe trace and photograph of microstructure of Rheocast X-40 cobalt base superalloy. Solute distribution is along dotted path shown in the photograph. Both the graph and the photograph have the same scale in the horizontal direction.

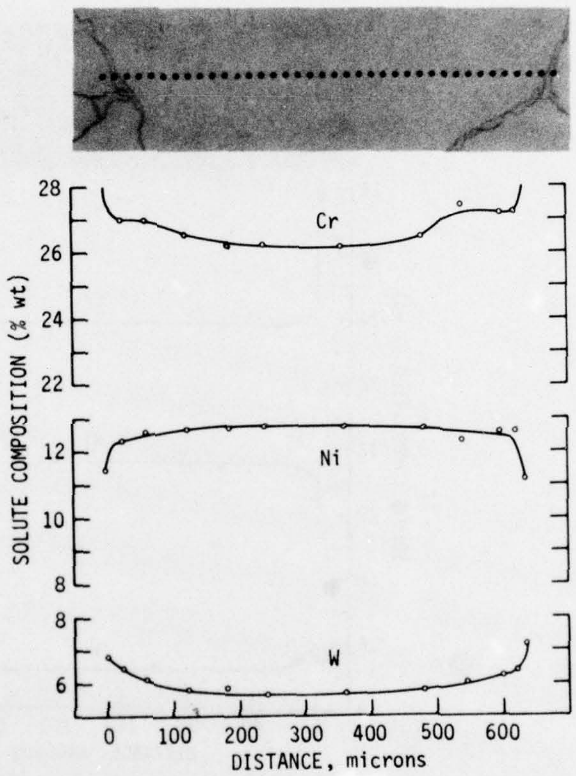


Figure 4. Composite figure showing microprobe trace and photograph of microstructure of Rheocast and homogenization heat treated (5 hours at 1300°C) X-40 cobalt base superalloy. Solute distribution is along dotted path shown in the photograph. Both graph and photograph have the same scale in the horizontal direction.

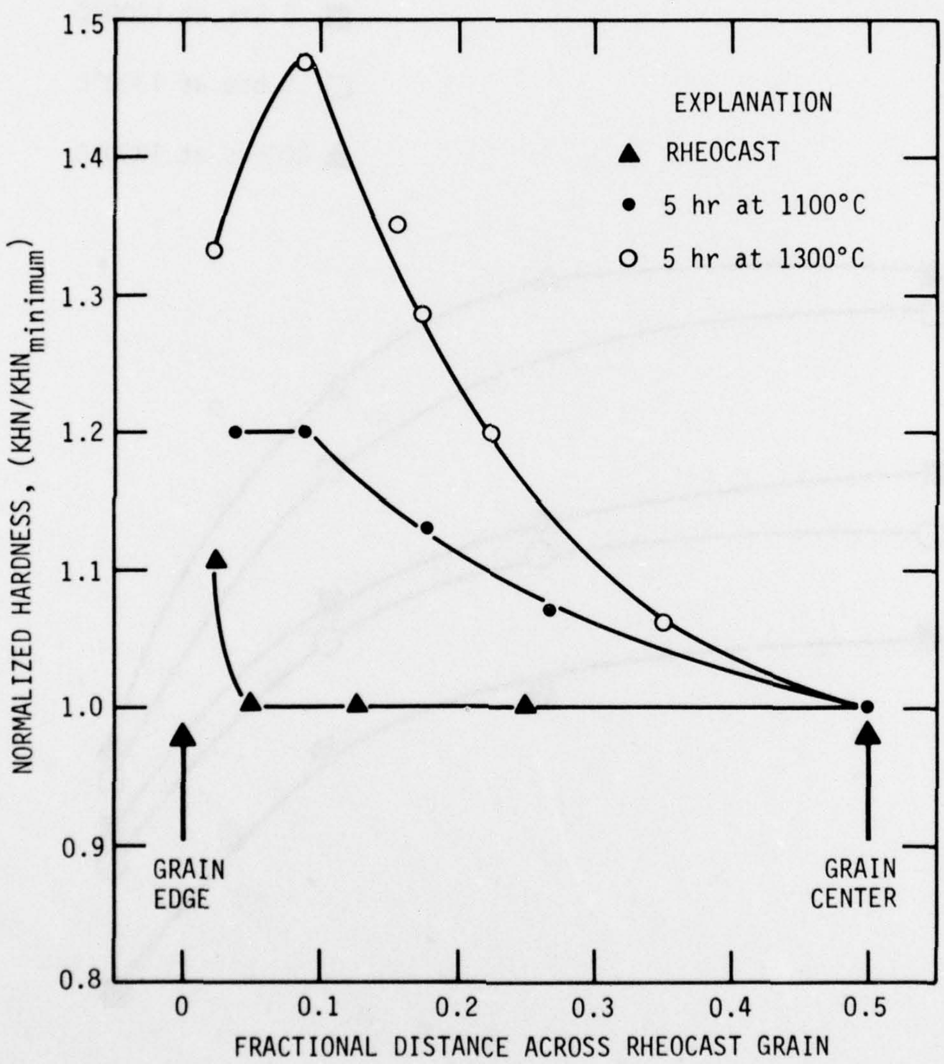


Figure 5. Measured variation of microhardness, normalized as the ratio of Knoop hardness number at a given location against the minimum value, across the Rheocast grain of X-40 cobalt base alloy in as-Rheocast and homogenized heat treated conditions.

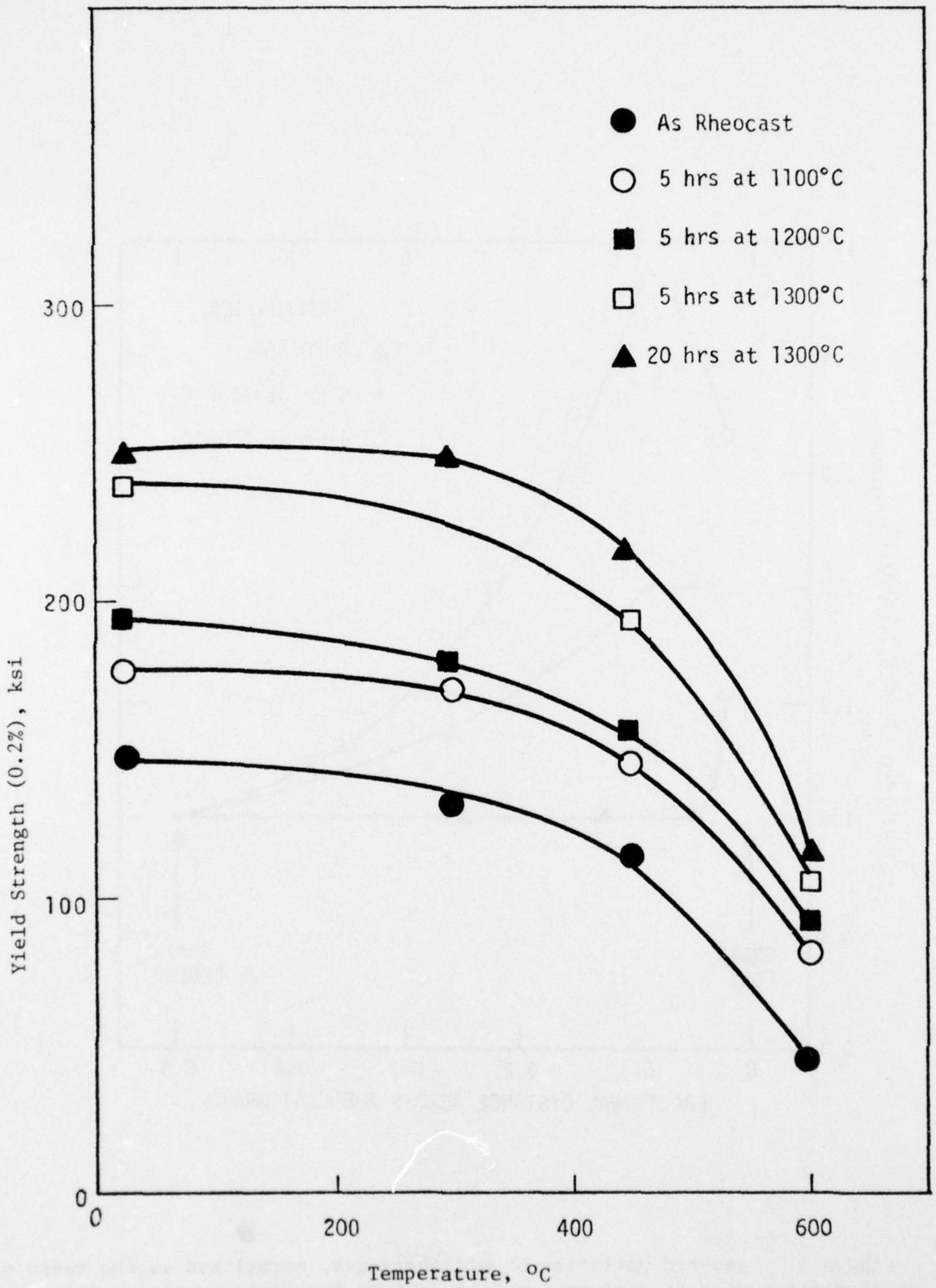


Figure 6. Measured compressive yield strength of as-Rheocast and homogenization heat treated 440C stainless steel as a function of temperature.

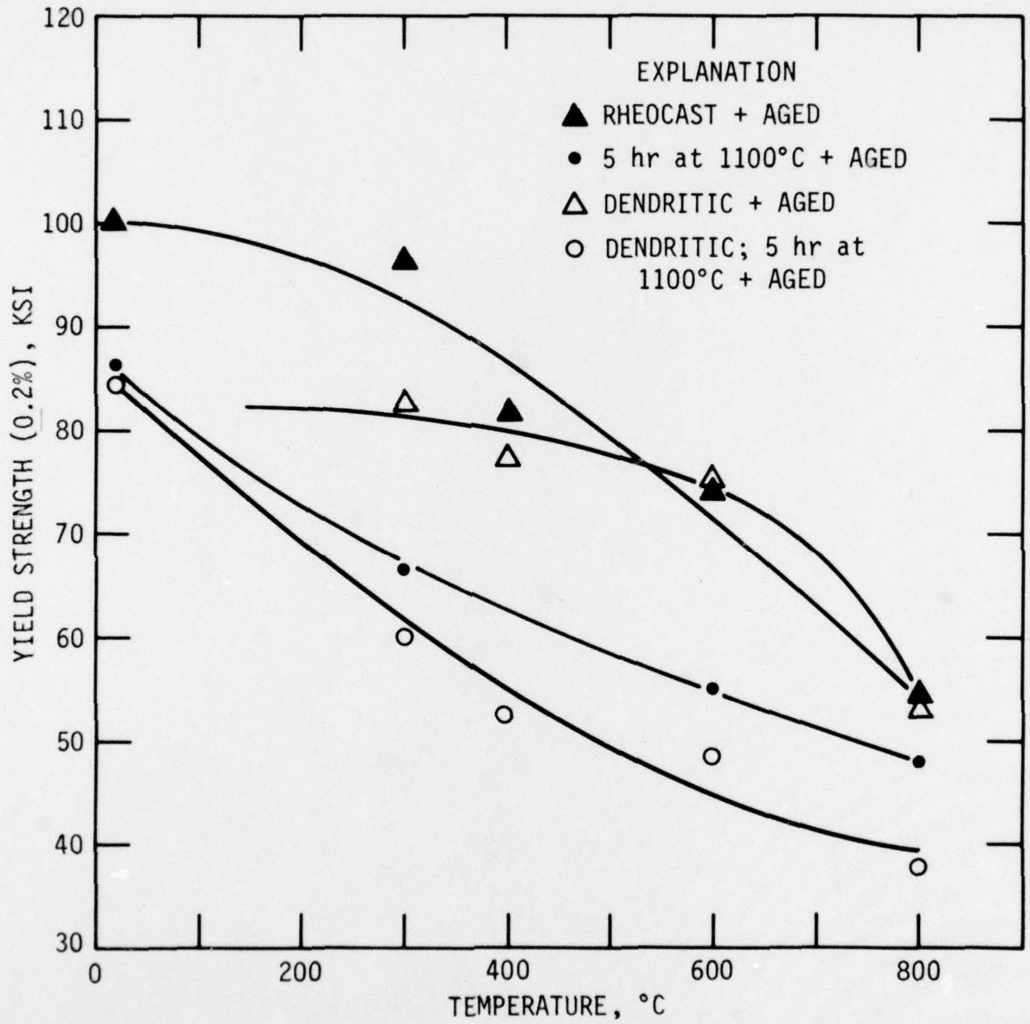


Figure 7. Measured compressive yield strength for dendritic and Rheocast X-40 cobalt base superalloy after two different heat treatments. (1) Aged at 700°C for 50 hours; (2) homogenized (5 hours at 1100°C) plus aging at 700°C for 50 hours.

MECHANICAL PROPERTIES OF THIXOCAST ALLOYS

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SUMMARY

Tensile test bars have been Thixocast in two alloys CDA 905 (88wt% Cu, 10wt% Sn, 2wt% Zn) and AISI 304 stainless steel. These bars exhibited microstructures typical of the bulk of Thixocastings at M.I.T. As-cast tensile strengths measured were equivalent or superior to the conventionally cast alloys with somewhat lower ductility.

As can be seen from the papers in this text, Rheocasting and associated processes afford a unique opportunity among other metal working processes to substantially manipulate the physical character of metals prior to full solidification. As one example Rheocasting processes offer a means of providing castings with a fine grain size controlled by the cooling rate in the Rheocaster and independent of the cooling rate in the mold. In addition both the primary solid particle shape and volume fraction may be varied. Furthermore, in many alloys such as M2 tool steel for instance, which can undergo extensive phase transformation within the solid/liquid temperature range, it affords the potential of significantly influencing the degree of that transformation again independent of the solidification in the mold.

Clearly then, there can be no single definitive characterization of the mechanical properties of alloys which are subject to Rheocasting processes. Recognizing the diversity of structures that can be obtained, emphasis at M.I.T. has been directed toward establishing prelimineary as-cast tensile mechanical properties for the Thixocast microstructure typical of the bulk of the castings made to date. So far, two alloys have been examined. One, the copper base alloy CDA 905 (88wt% Cu, 10wt% Sn, 2wt% Zn) which has been used extensively as a model alloy for Thixocasting development and AISI 304 stainless steel.

Preforms for cylindrical tensile test bars, 4" long by 3/8" diameter were Thixocast at 0.50 volume fraction solid into steel dies at 250°C. Modified ASTM standard cylindrical tensile test bars with a 1-3/4" reduced section and 1/4" gauge diameter were then cut and pulled at room temperature on an Instron machine using a cross-head speed of 0.2 in-min^{-1}.

The preliminary results for the two alloys are shown in Figures 1 and 2. For both alloys the average ultimate tensile strength and yield strength are equivalent or superior to the conventionally cast (e.g., investment or sand cast) alloy. Ductility in both Thixocast alloys is lower than the equivalent sand cast data and comparable to that for the chill cast alloy. In light of the fact that the structures tested were in no way optimized for mechanical performance, these results are considered extremely encouraging.

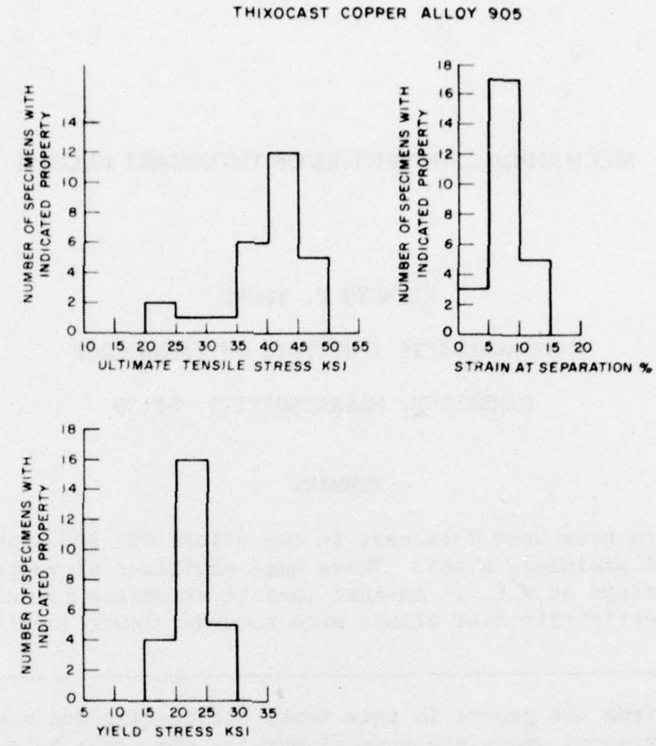

Figure 1: Preliminary tensile test results from Thixocast bronze alloy CDA 905 (from Goodwin).

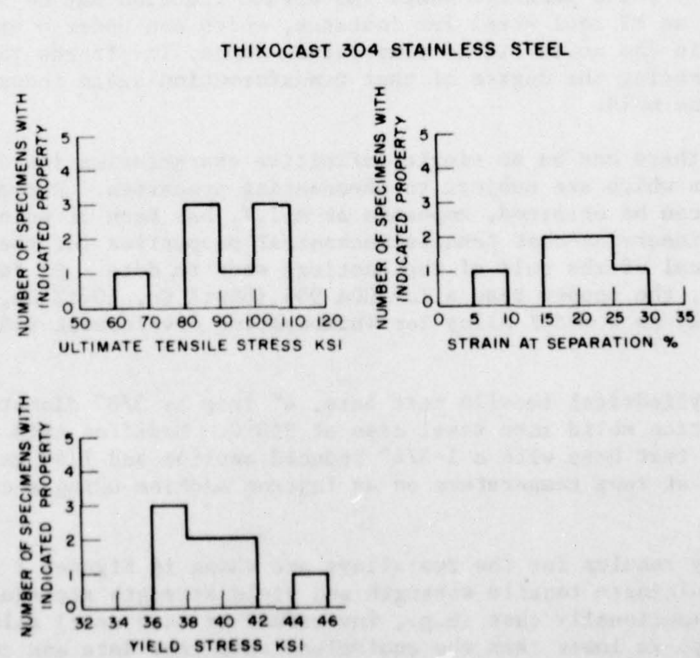

Figure 2: Preliminary tensile test results from Thixocast AISI 304 stainless steel (from Goodwin).

This is especially so since preliminary data suggests that the Thixocast microstructure should respond well to heat treatment.

Finally, in addition to this ongoing investigation of the mechanical properties of Thixocastings, M.I.T. is also engaged in a few exploratory investigations of other processing routes. One of these has been a limited investigation of the extrudability of Rheocast 304 stainless steel in co-operation with I.I.T. (Harper) Corporation. Small billets 6" long by 1-3/8" were Rheocast at M.I.T. and hydrostatically extruded (4.6:1) at a temperature of 900 - 950°C. The tensile properties obtained from bars cut from the extruded rods are shown in Figure 3. They compare well with those of hydrostatically extruded wrought material and are superior to that of conventionally cold worked rod.

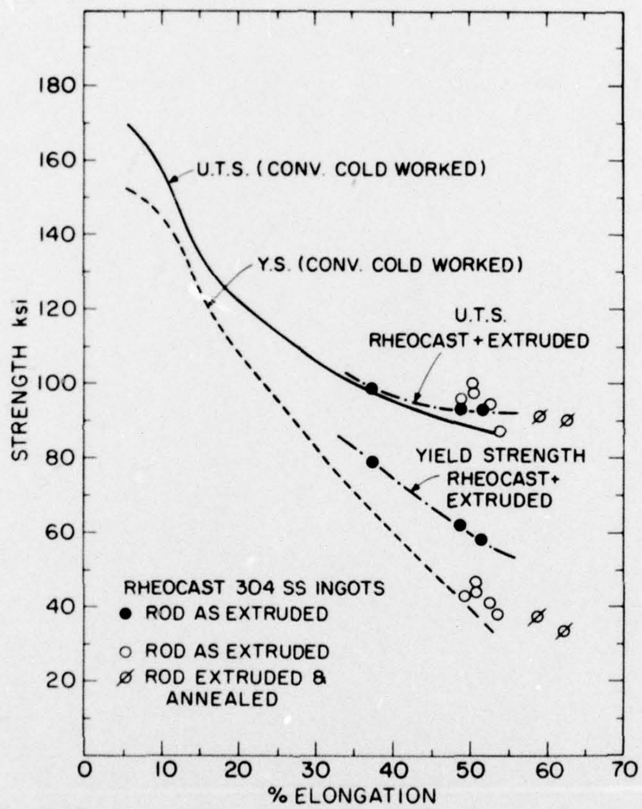

Figure 3: Mechanical properties of hydrostatically extruded Rheocast 304 stainless steel compared with the conventionally cold worked and hydrostatically extruded wrought material.

MACHINE CASTING OF HIGH TEMPERATURE ALLOYS

L. F. Schulmeister, J. D. Hostetler, C. C. Law and J. S. Erickson

Pratt & Whitney Aircraft Group

Commercial Products Division

INTRODUCTION

The objective of this program is to evaluate the suitability of machine casting, in particular thixocasting, for the fabrication of low cost, high quality ferrous and superalloy turbine engine components, such as airfoils. These items are currently manufactured by investment casting or forging techniques. A machine casting process offers the potential for producing quality airfoils at significant cost savings over existing fabrication methods for the following reasons: 1) production economies similar to die casting through automation; 2) product reproducibility through precise control of processing parameters; and 3) reduced finishing requirements associated with good surface quality and close dimensional control.

The information presented here has been generated on the DARPA-AMMRC Contract DAAG76-46-C-0029 "Machine Casting of High Temperature Alloys" and is to be regarded as an interim progress report.

EQUIPMENT DESCRIPTION

The machine casting unit used in this program is a converted injection molding press (Figure 1). The rheocast preform is heated by a direct induction coupling and upon

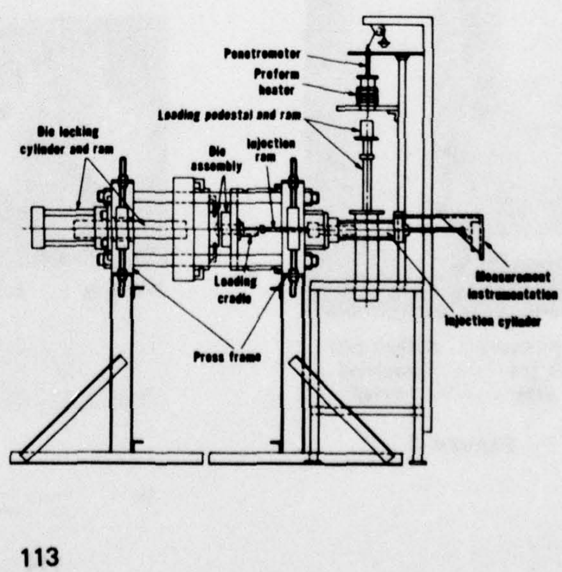

Figure 1 - Machine Casting Unit

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reaching the proper temperature/volume fraction solid, as determined by a weighted penetrometer, is hydraulically lowered from the heater. It is then manually transferred to the loading cradle in the press. The injector is actuated (5 ton pressure with accumulator), and the preform is injected into the die set (25 ton locking pressure) at a maximum speed of 30 in/sec. The die assembly, made from H-11 tool steel, contains a machined cavity for producing a simulated airfoil shape (Figure 2).

For the preform container, an alumina-silica shell molded tube with a Fiberfrax bottom insert, was found to be the most satisfactory means for holding and transferring the preform to the press cradle (Figure 3). Fiberfrax cups were found to contaminate the injected part, while mullite tubes with Fiberfrax bottoms cracked due to thermal shock.

MACHINE CASTING TRIALS

Injection Trials

X-40, an air-melted cobalt-based superalloy, was selected for the majority of injection trials, as it represented a reasonable balance between availability (in the rheocast form) and applicability. It was supplied to MIT in bar form to be rheocast in their continuous casting unit. A typical microstructure of the MIT rheocast product is shown in Figure 4.

Initial injection trials have been run using the simulated airfoil die to study the effects of such variables as volume fraction solid (Figure 5) and die temperature. The material produced from these runs cannot be considered to be representative of the quality which the process is ultimately capable.

Analysis of Parts

Both radiographic and metallographic analyses were performed on these initially injected airfoils. It appears that as the volume fraction solid increases, the degree of internal porosity decreases as determined by radiographic analysis (Figure 6).

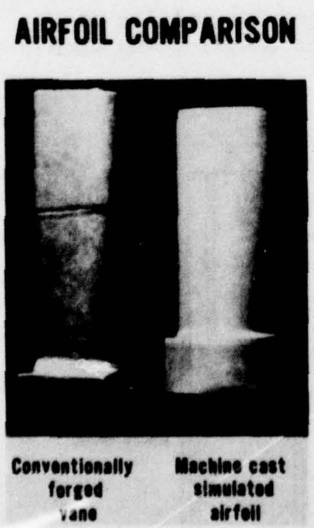


Figure 2

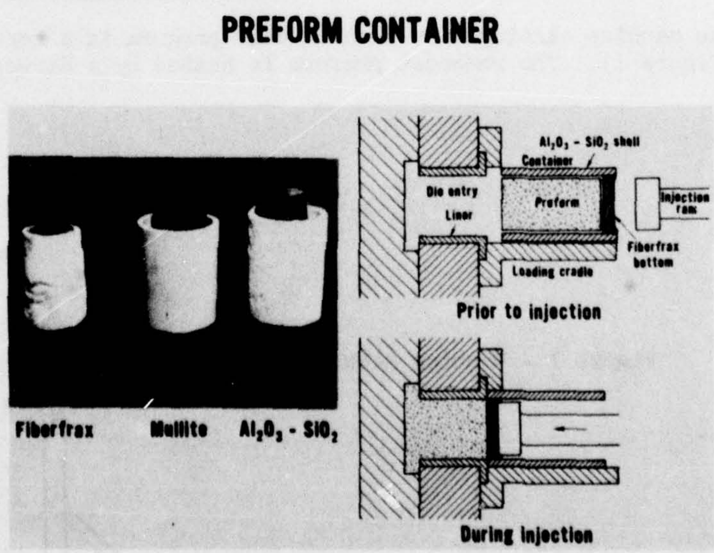
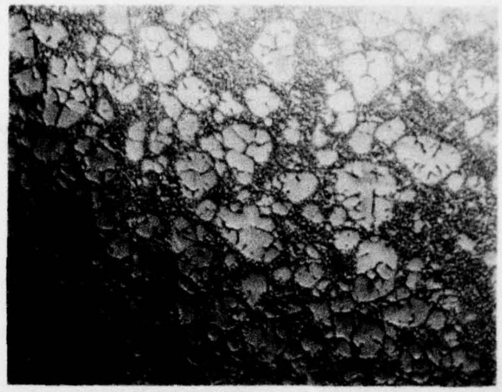


Figure 3

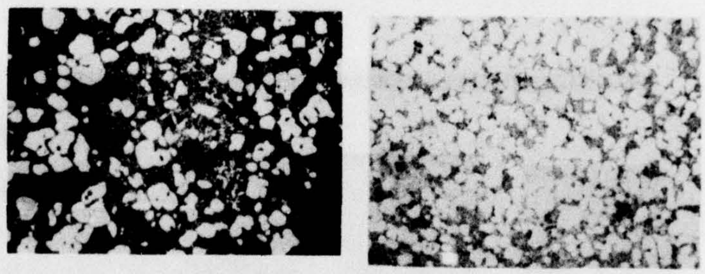
RHEOCAST X-40

Figure 4



PREFORM VOLUME FRACTION SOLID

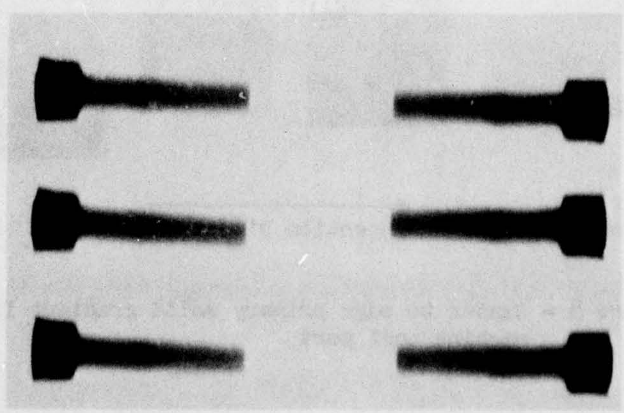
Figure 5



Low v/o solid **High v/o solid**

MACHINE CAST PART RADIOGRAPH

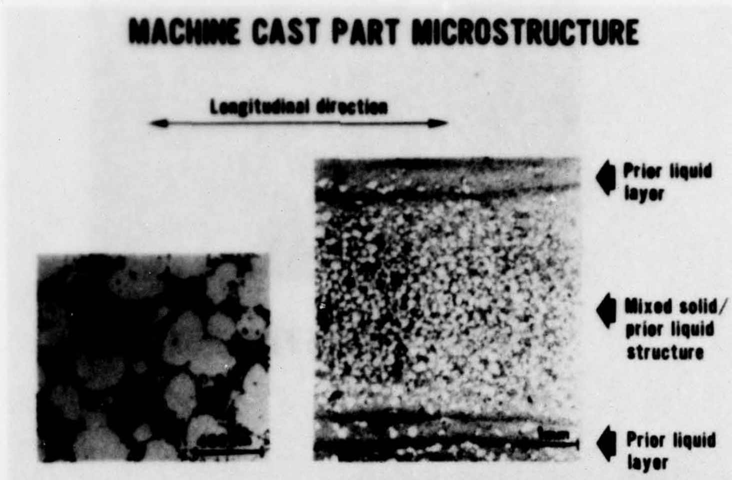
Figure 6

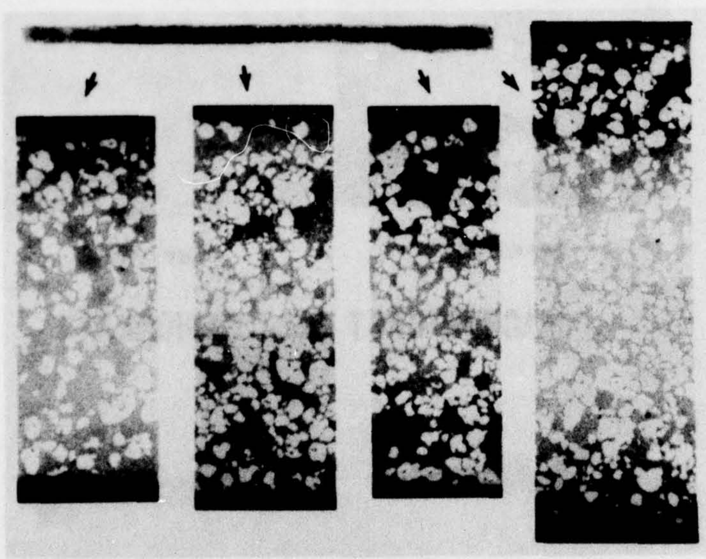


Low v/o solid **High v/o solid**

Metallographic analysis of low volume fraction solid (< 40%) airfoils showed a distinct layering effect which consisted of a nearly 100% prior liquid layer near the surface of part and a mixed primary solid/prior liquid structure underneath (Figure 7). Higher volume fraction solid parts (> 50%) contained a less distinct layering effect; however, there was a gradient of percent primary solid from center to edge as shown in Figure 8. This effect is being studied further.

Figure 7





Upper Airfoil

Injection Direction

Root

Figure 8 - Center to edge primary solid gradient in machine cast part

Preliminary Mechanical Properties

Room Temperature and 1450°F tensile tests were performed on flat specimens taken from the simulated airfoils produced during the initial injection trials. Representative results are listed in Table I. Room temperature tests achieved strength and ductility goals. Tests run at 1450°F achieved yield strength goals, while ultimate strength and ductility goals were nearly reached.

Table I - Tensile Properties of Machine Cast X-40

Tensile Specimen	Temp (°F)	Y.S. (ksi)	UTS (ksi)	El (%)
1	R.T.	78.7	102.5	7.2
2	R.T.	88.3	119.2	5.0
Goal	R.T.	50.0	83.0	4.0
3	1450	41.0	54.5	6.0
4	1450	38.1	53.4	6.8
Goal	1450	24.0	58.0	8.0

Stress rupture testing was also performed on specimens taken from simulated airfoils. In as-cast materials rupture lives were low; however, cast and hot isostatically pressed (HIP) specimens surpassed rupture life goals. Representative data are presented in Table II. HIP is presumably beneficial because it closed porosity in the injected part and/or caused a structural improvement due to the thermal cycle associated with the HIP operation itself. This behavior will be studied further.

Table II - Stress-Rupture Properties of Machine Cast X-40 Tested at 1450°F/30 ksi

S/R Specimen	Condition	Rupture Life (Hrs)
1	As-Cast	4.7
2	As-Cast	8.5
3	As-Cast + HIP*	28.7
4	As-Cast + HIP*	35.7
5	As-Cast + HIP*	42.1
Goal		30.0

*2215°F/15 ksi/4 hours

CONCLUSIONS

A machine casting unit, converted from an existing injection molding press, has been used to fabricate simulated airfoils out of rheocast X-40, a cobalt-base superalloy. Increasing the volume fraction solid in the rheocast preform prior to thixocasting improved the radiographic quality.

Tensile and stress rupture tests on specimens taken from the simulated airfoils produced during initial casting trials reached, or nearly reached, targeted goals. Additional parametric and mechanization studies are planned together with further characterization of the product from the machine casting unit.

SESSION IV

APPLICATIONS AND ECONOMIC OUTLOOK

Session Chairman

M. Sinnott
University of Michigan

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RHEOCAST® CORPORATION A COMMERCIAL VENTURE

Wendell T. Hess

Rheocast Corporation

THE COMPANY

Rheocast Corporation was incorporated in Massachusetts in 1973 for the purpose of developing and commercializing a new technology for the die casting or forging of metals. In 1975, the company was financed by an influx of venture capital from private investors. Rheocasting (the Process) was invented by Professors Merton C. Flemings, Robert Mehrabian and their associates at M.I.T. under contract to the U.S. Army Research Office, Durham, N.C. The Company has a limited term exclusive license from M.I.T. for patents and patent applications which have been filed on the Rheocasting and related technology. The government for its own use has the right to use the Rheocasting technology. Large tonnage markets exit in brass and bronze alloys which are presently sand cast at temperatures over 2,000 degrees Farenheit, and cannot, at present, be economically die cast. Die casting or machine forming of these alloys using Rheocasting technology the Company believes, will provide substantial economic advantage over other casting and forming processes.

The Company occupies 20,000 square feet in a modern plant located in Natick, Massachusetts. The facility is equipped with melting, Rheocasting, die casting, finishing and heat treatment equipment. Tool and die maintenance is done in the company's own facility and quality assurance includes complete mechanical testing, chemical and metallurgical analysis capabilities with qualified personnel.

THE BUSINESS

The Company is engaged in scale up of the Rheocast process for commercial use. This involves designing, building and testing metal shearing and cooling equipment for metal systems including lead, zinc, magnesium, aluminum, copper, cast iron, steel and super alloys. At present, a major effort is directed to copper alloy die casting. This involves entering into contract development activities to evaluate specific part applications, making die castings and billet material for sale, building Rheocast equipment for sale and licensing the process to potential users. The company expects to be in full scale part production by mid-year.

MARKET

The market for copper base alloy castings (that is all that is being considered here) according to the American Die Casting Institute figures and other sources breaks down in the following manner:

U.S. Annual Copper Alloy Part Castings			
Sand Casting	667,000,000	pounds	85.5 Percent
Permanent Mold	33,000,000	pounds	4.2 Percent
Die Casting	23,000,000	pounds	3.0 Percent
Other Including Investment	57,000,000	pounds	7.3 Percent
	780,000,000	pounds	100.0 Percent

This tonnage represents a 1.6 billion dollar market. Approximately one-half of the tonnage represents castings under 20 pounds in weight and in alloys suitable for die casting. For economic reasons only three percent of the market is now die cast. This three percent has a present end use as shown below:

Copper Alloy Die Cast End Use

	Percent	Alloys
Industries and Commercial Machinery and Tools	21	Yellow brass, engineered bronze
Office Equipment and Business Machines	3	Bearing bronze
Plumbing, Heating and Builders Hardware	72	Red and yellow brass
National Defense	2	Bearing bronze, engineered bronze
All Other	2	
	100.0	

There exists large opportunities for technical reasons already discussed in other presentations, to machine cast many parts now made as sand castings and to produce parts near to finished shape and dimensions with substantial savings in machining and energy costs. Rheocast is currently concentrating on this market and more specifically manufacturing of parts of o.1 to six pounds in weight. A series of parts *including valve assembly parts*, electrical hardware and decorative hardware were illustrated in a slide presentation.

ECONOMIC ANALYSIS

To illustrate the type of economic savings which can be realized in going to machine casting, a specific example which has been tooled and evaluated will be reviewed. The part for many years has been produced as a sand casting and by die casting a reheated Rheocast slug realized substantial savings in metal alloy, reduced final machining and conservation of energy. Cost comparison is done on a direct cost to manufacture basis with no overhead or profit. The part used in this illustration is made in large volume and represents a very competitive part.

Sand Cast	22 parts/pound as cast	Machined weight 74% cast weight
Rheocast	51 parts/pound as cast	Machined weight 88% cast weight

Direct Costs to Manufacture

Since the actual part pricing is proprietary the costs to manufacture are expressed in terms of percent of total cost. In this case the Rheocast process represents a savings of 12 percent in the direct cost to manufacture.

	Rheocast	Sand Cast
Casting	47.0%	42.8%
Tooling	16.2%	2.0%
Finishing	5.4%	18.0%
Metal alloy	28.5%	37.2%
conversion	2.4%	--
royalty	.5%	--
	100.0%	100.0%

It should be mentioned that the melt losses experienced when handling semi-solid metals are considerably reduced from those normally experienced for super heated liquid metal. Experience has shown that reduced metal oxidation and losses aids greatly in controlling composition and reduced part rejection losses.

SUMMARY

It should be stressed that great strides have been made in improving the Rheocast process metal alloy systems particularly for copper and aluminum alloys. The systems at Rheocast operate either in air or with a protective atmosphere in all critical areas. Current production rates are typically 20 to 30 pounds per minute. While no regular melting and Rheocasting of ferrous alloys is done at Rheocast Corporation, heats of iron-nickel alloys have been made as part of development programs. Similarly the facilities exist to make experimental quantities of composite materials for product evaluation. The company prefers to operate this business on an engineered materials basis.

ECONOMIC ASPECTS OF RHEOCASTING

R. Mehrabian

University of Illinois, Urbana-Champaign, Illinois

ABSTRACT

An economic study has been initiated to evaluate the economics of the high temperature alloy machine casting process (Thixocasting). A cost breakdown model has been developed that permits estimation of cost per piece for manufacture of parts by the new machine casting process.

I. INTRODUCTION

The general aim of this study is to evaluate the economics of the high temperature alloy machine casting process (Thixocasting) and to develop a model to project and compare cost per piece with established methods of manufacture. In the first phase of this work a cost breakdown for manufacturing of parts by the new machine casting system was developed. The costing technique, presented herein, permits calculation of projected cost per piece for a given part. Work is presently underway to (1) identify a number of parts procured by the Department of Defense that would be amenable to machine casting using the Thixocasting process, and (2) obtain current or past manufacturing cost for the parts identified.

II. COST BREAKDOWN

Cost associated with the manufacture of parts by the new machine casting process (Thixocasting) is subdivided into specific sequence of operations:

(a) Die design, tooling and set-up*;

(b) Melting and Rheocasting - billets produced are of appropriate diameter to fit in the shot sleeve of the casting machine;

(c) Ingots are cut to appropriate lengths for machine casting**;

(d) Reheating to liquid plus solid temperature range and machine casting;

---

*Die maintenance cost per piece will be considered in the die tooling cost--of course, total die life would be an important item in cost per piece.

**In a continuous production operation the slurry producer could be combined with a continuous casting machine. The emerging billets could then be cut to the appropriate lengths in a single operation in phase with the casting rate.

(e) Castings are cut off the runners and biscuit;

(f) Rough inspection;

(g) Heat treatment - if required in specifications;

(h) Machining and finishing;

(i) Magnaflux/Zyglo inspection - if required in specifications;

(j) X-ray - if required in specifications;

(k) Certification - chemical and/or mechanical - if required in specifications.

The sequence of manufacturing operations is broken down in direct material and direct labor costs. Some of the usual manufacturing overhead costs (e.g., utilities, service and maintenance, employee benefits) are considered part of the direct material and direct labor costs. The other manufacturing overhead costs (e.g. administration, marketing, research, sales, profits, etc.) are unique to the manufacturer, hence are not included in this cost analysis. Direct materials and labor costs incurred in the sequence of operations (a) through (d) are estimated from the work sheets for:

Estimated Rheocast Metal Cost

Estimated Metal Cost Per Piece

Estimated Reheating and Die Casting Cost

Details of these work sheets are shown in the following pages.

The cost of capital equipment is included by calculating the amortized capital equipment cost from Table I.

$$\text{Amortized Capital Equipment Cost/Piece} = \frac{\$16,500.00}{\text{\# of pieces to be made per year}}$$

Finally, an important input in the cost analysis is cost and life of machine components, especially die life. A pilot plant machine casting operation for Thixocasting of stainless steel alloys is presently underway at M.I.T. as part of this program. It is anticipated that actual measured die lives will become available for inclusion in the economic study before the completion of the program.

Work Sheet - Estimated Rheocast Metal Cost

Alloy Cost/lb. + (Melting Cost + Rheocasting Cost)/lb. =
__________ + ____________________________ =
Rheocast Metal Cost/lb.
____

Melting Cost in an investment foundry using a 500 lb. induction furnace is approximately 10¢/lb. This figure includes labor and overhead, furnace linings, melt losses, etc.

Rheocasting Cost includes the additional cost of special crucibles, rotors, thermocouples, etc. Assuming simultaneous melting and Rheocasting (as in a continuous slurry producer) at a casting rate of approximately 500 lbs/hr, the estimated cost for Rheocasting would add approximately 4¢/lb. to the above melting cost.

Work Sheet - Estimated Metal Cost Per Piece

A. Net Metal Cost Per Shot

Pieces/Die x lbs/Piece + lbs/G,R,B,& O* =

__________ x ________ + ______________ =

lbs/shot x Rheocast Metal Cost/lb = Gross Cost - lbs x (G,R,B,& O) x Scrap Price

_______ x _____________________ = _________ - ________________ x ___________

= Net Cost

= ______

B. Net Metal Cost Per Piece

Net Cost ÷ Pieces/Die = Net Cost/Piece

______ ÷ __________ = _____________

*G,R,B,& O designate gates, runners, biscuit and overflows.

Work Sheet - Reheating and Casting Cost Per Piece

Labor (fringe + utilities) ÷ (Shots/hr x Pieces/Die)

________________ ÷ (______ x ______)

+ Die Cost/Piece + Shot Sleeve Cost/Piece + Plunger Tip Cost/Piece

+ ________ + ____________ + ____________

+ Lubricant Cost/Shot ÷ Pieces/Die = Cost/Piece

+ ____________ ÷ ______ = ______

Shots/hr would include die set-up time.

Die cost includes the total cost for design and fabrication of the die and die maintenance cost for the duration of die life. Assuming that a given die has multiple casting cavities, then

$$\text{Die Cost/Piece} = \frac{\text{total die life}}{\text{pieces/die x die life}}$$

$$\text{Shot Sleeve Cost/Piece} = \frac{\text{cost of shot sleeve}}{\text{pieces/die x shot sleeve life}}$$

Table I

CAPITAL EQUIPMENT COST FOR PILOT PLANT MACHINE CASTING OPERATION

Description	Purchase Price and Installation ($)	Write-Off Period (Years)	Annual Depreciation ($/year)
One 100 KW and one 50 KW induction power supply for Rheocasting	54,000.00	15	3,600.00
Continuous Rheocasting Machine	20,000.00	10	2,000.00
One 50 KW induction power supply for slug reheating	26,000.00	15	1,733.33
Instrumentation for Rheocasting and Machine (Die) Casting	25,000.00	10	2,500.00
400 ton die casting machine	80,000.00	12	6,666.66
TOTAL	$205,000.00		$16,500.00

The equipment needed for pilot plant manufacturing of ferrous parts using the machine casting (Thixocasting) process include the following:

(i) A continuous slurry producer including two induction power supplies (one each for the upper holding and lower mixing chambers).
(ii) A slug reheating furnace (induction coils and softness tester) and an induction power supply.
(iii) Instrumentation; multi-channel temperature recorder, visicorder and associated equipment.
(iv) Die casting machine.
(v) Trimming press (or cut-off wheel), machining and finishing equipment normally used in an investment foundry or a low temperature metal die casting operation.

PRELIMINARY ECONOMIC CONSIDERATIONS FOR THE MACHINE CASTING OF GAS TURBINE AIRFOILS

L. F. Schulmeister

Pratt & Whitney Aircraft Group

Commercial Products Divisior

INTRODUCTION

A preliminary analysis of the costs of gas turbine airfoils fabricated by either forging or investment casting indicates that in both processes the most significant cost factor is finishing. The economic potential for the machine casting or, in this case, thixocasting of airfoils is contingent on the ability of the process to produce dimensionally finished or net shaped parts which reduce the finishing cost burden. Prior work in conventional die casting sponsored by P&WAG indicated the potential to produce parts to near finished shape (Figure 1).

COMPARISON OF FORGING AND MACHINE CASTING

The forging of airfoils consists of converting bar stock through several forming steps into an airfoil shaped envelope. The envelope, including the root attachment, is then finish machined. These finishing costs are estimated to comprise over three-fourths of the total part cost (Figure 2). Machine casting can potentially reduce these finishing costs by as much as one-half because of the ability to produce parts which require minimal post conversion processing. It is assumed that process yields

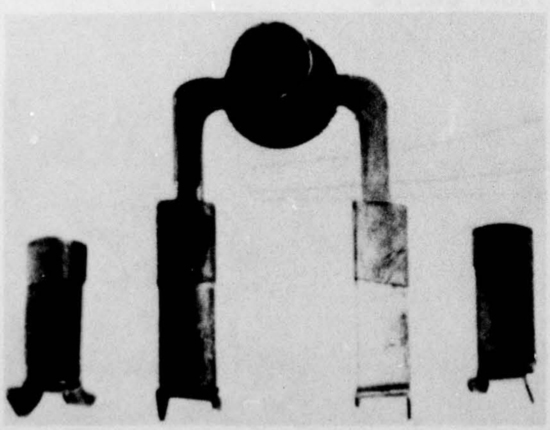
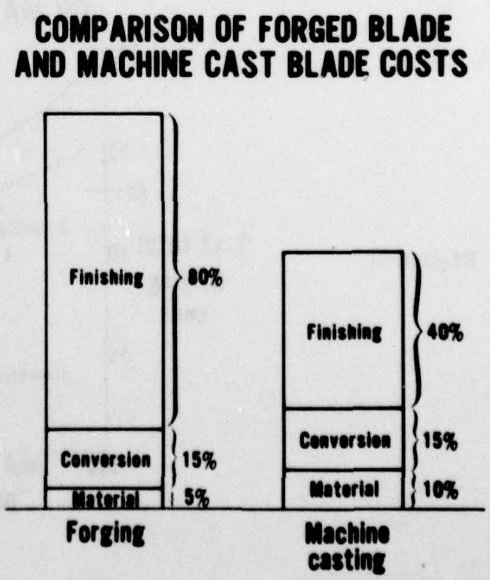


Figure 1 - As Die Cast and Forged and Finished Compressor Airfoils

Figure 2



are similar, and that no property debits exist. Material and conversion costs for both processes are expected to be similar.

The sensitivity of overall cost to variations in the above three cost categories is shown schematically in Figures 3, 4 and 5. A wide variation in input material cost (Figure 3) should have little effect on finished machine cast part costs. Conversion cost or, more specifically, die cost should not be a critical factor if, in the case of expensive dies, lifetimes are reasonably extensive (Figure 4).

Figure 3

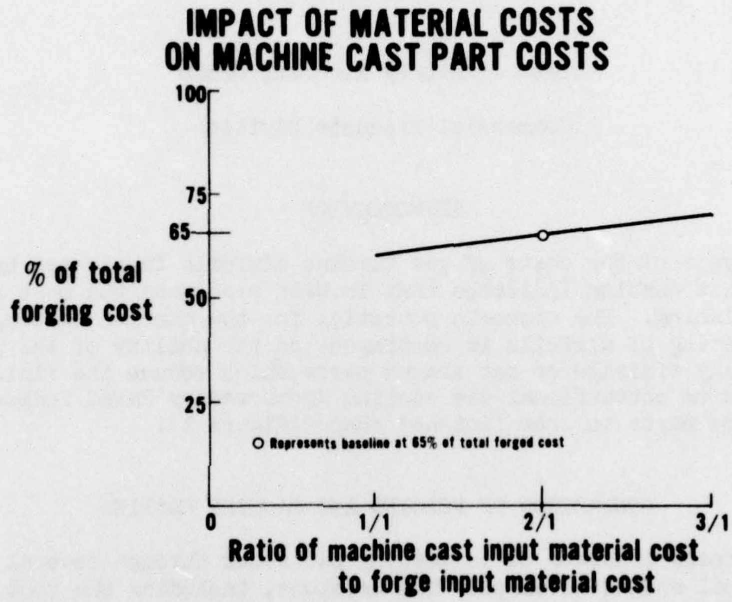
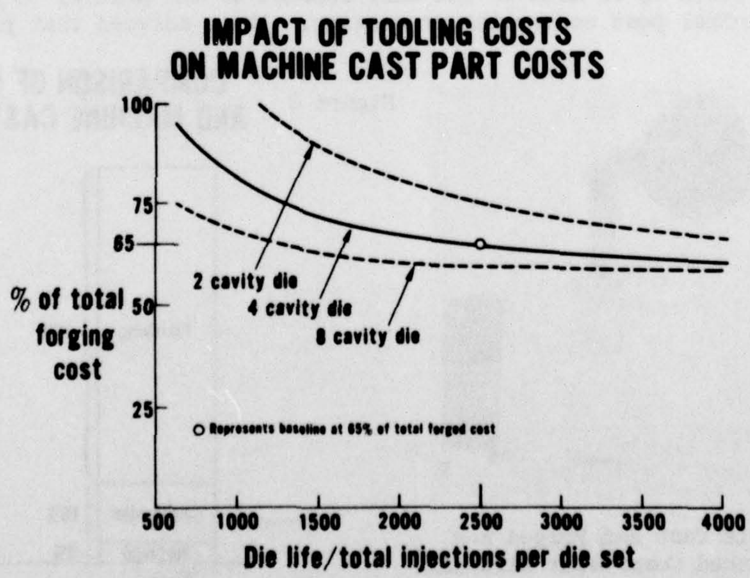


Figure 4



The primary economic impact of machine casting resides in the finishing cost area as shown in Figure 5. Any significant deviation from achieving net or near net shape will adversely affect the cost savings that could be generated by using the machine casting process in place of forging for airfoil fabrication.

COMPARISON OF INVESTMENT CASTING AND MACHINE CASTING

A similar preliminary cost analysis has been made for the investment casting of airfoils. It is estimated that approximately two-thirds of the part cost for investment casting is in the area of finishing (Figure 6). A large portion of this cost in turn is associated with the extensive and expensive set-ups for finish machining of cast airfoils. Finishing costs for machine cast parts will be affected

Figure 5

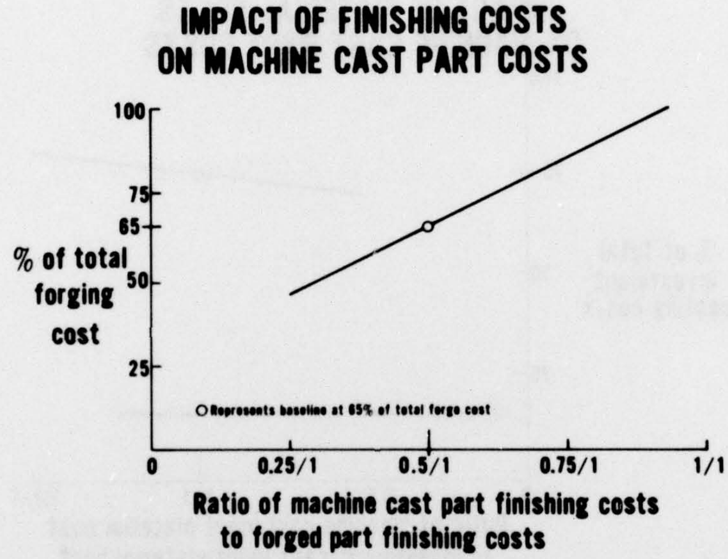
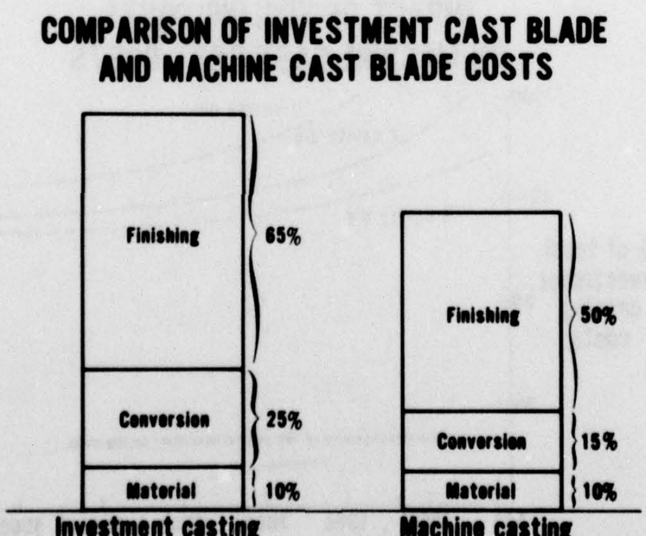


Figure 6

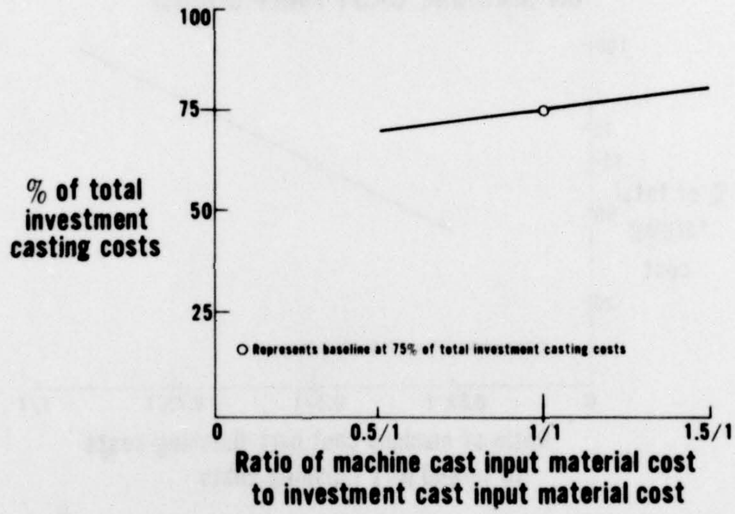


by the same set-up costs for detail finishing in investment castings thus savings are not anticipated to be as extensive as in the forging comparison made above. The conversion costs shown in Figure 6 include some post cast processing work which is done prior to machining. Conversion costs for machine cast parts are projected to be less than those for investment casting, primarily due to a reduction in the post-cast processing costs which are included in the conversion area. Material costs will probably be similar in both processes.

The projected impact of variations in these three cost components (Figures 7, 8 and 9) on the overall cost is similar to the study performed for machine casting versus forging. Materials cost changes should have minimal effect (Figure 7) while die cost variation would have effects similar to the previous analysis (Figure 8). Again, the primary economic potential of the machine cast process is to be realized in the area of finishing costs (Figure 9). This, however, is not felt to be as great as in the case of machine cast versus forged parts.

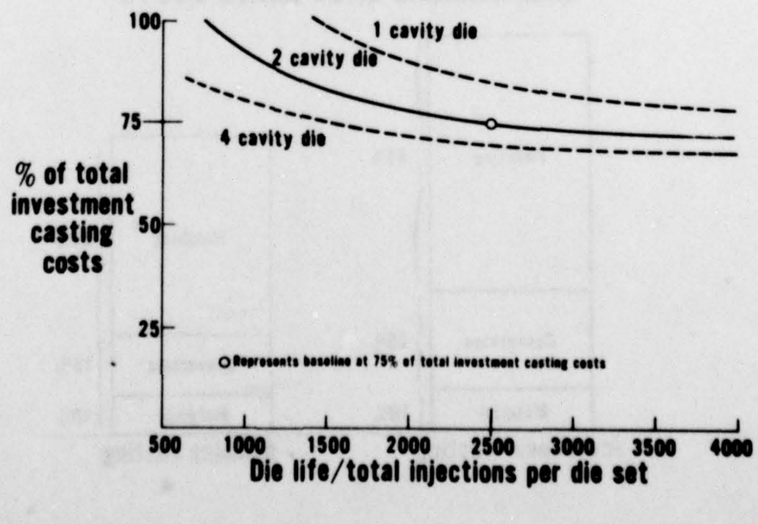
IMPACT OF MATERIAL COSTS ON MACHINE CAST PART COSTS

Figure 7



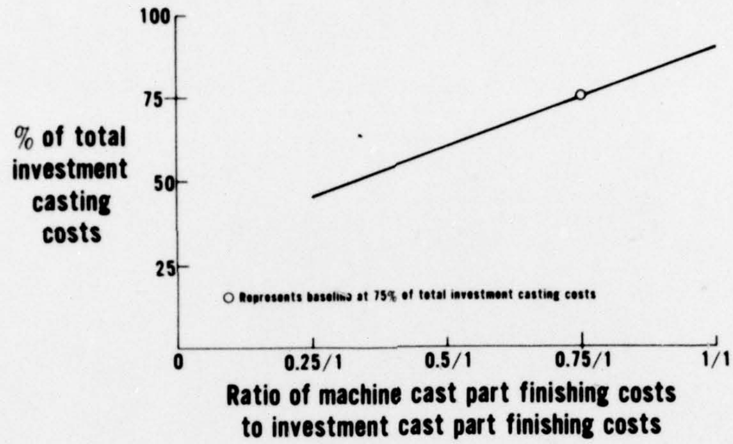
IMPACT OF TOOLING COSTS ON MACHINE CAST PART COSTS

Figure 8



IMPACT OF FINISHING COSTS
ON MACHINE CAST PART COSTS

Figure 9



CONCLUSIONS

The concept of net shape forming is the primary ingredient in any potential cost effectiveness which the machine casting process may possess. A comparison of machine casting to forging indicates that the former process may be able to save 30-40% of the finished part cost because present forging techniques do not produce a net or near-net shape airfoil. For the case of machine casting versus investment casting, savings on the order of 25% may be possible; but the cost motivation becomes less and less attractive the closer investment cast parts can be made to net shape.

SESSION V

PANEL DISCUSSION

Session Chairman

R. D. French
Army Materials and Mechanics Research Center

PANEL DISCUSSION

"What should the respective roles of industry and Government be in the future development of Rheocasting and related secondary processes?"

Chairman: R. D. French (AMMRC)

Panel: A. Bement (DARPA), R. Spear (Alcoa), M. Flemings (MIT), W. Hess (Rheocast Corporation), M. Kenney (ITT), R. Mehrabian (University of Illinois)

In the earliest stage of development, Rheocasting was considered to be a type of die casting process, and, as such, included a shape forming step. Since that time, it has become more convenient to view Rheocasting as a melting process which produces materials with a unique microstructure. The reasons for this lie in the many opportunities afforded by related developments such as Compocasting, Thixocasting and Thixoforging.

With so many developments, each with its own potential for growth, it becomes difficult to satisfy everyone's interests with a single development program. Therefore, it is important that industry's interests in these developments are known and that industry's guidance is sought to assist DoD planning for the further development of Rheocasting and related secondary processes.

During the discussion period, the panel members unanimously expressed optimism about the future of Rheocasting and related processes. One of the panel members drew a comparison between the development of Rheocasting and the development of continuous casting of steel. He then expressed the thought that if the same engineering was put into Rheocasting that had been applied to continuous casting, Rheocasting would leap in its applications, an interesting point to consider.

Of course the engineering problems should not be minimized, but scaling the Rheocasting process for aluminum to at least thirty-inch diameter ingots was seen by the Panel as feasible. In this case, the advantage of Rheocasting would be a finer matrix microstructure than that produced by conventional processing with a possible subsequent benefit in a lower energy requirement for secondary processing. Ingots up to seven inches in diameter have already been made with some success.

Composites were discussed at some length; but, like Rheocast, Thixocast, and Thixoforged materials, more mechanical property data are needed. Properties, economic information, and the availability of material were, in fact, the principal issues raised.

The acceptability of mechanical properties is actually established during the design of new hardware; and, at that point, mechanical properties and cost can be adjusted against each other. This rather important point was made by representatives of the turbine engine industry when no firm answer was forthcoming from a discussion over the relative importance of specific properties and cost. This same industry, however, has the most stringent requirements for quality, and several statements were made which showed that Thixocasting and Thixoforging are being considered for competition with forgings and investment castings. Certainly, then, to the die casting industry the availability of Rheocast material has the potential of being a strong supplement.

A few members of the die casting industry have been involved with Rheocasting since its earliest days. During the discussion session it became clear that the investment casting industry would also be interested in developing a Rheocasting or Thixocasting capability if user acceptance could be demonstrated. Users, on the other hand, are hampered in their evaluation of the process and the material produced by the lack of suppliers. The existing industry involvement in Rheocasting is concentrated on aluminum and copper alloys and will not satisfy the users interested in steels and the superalloys.

In answering the question posed for the panel session, then, private industry has become involved in the development of Rheocasting and Thixocasting for aluminum and copper alloys. The DoD development program, however, will continue to be regarded in the near term as the principle source of information on the application of Rheocasting and related processes to steels and the superalloys. The goal of this program is to generate sufficient information to allow for industrial evaluation at the earliest possible date. Toward that end it was recommended that industrial involvement in the DoD program, including both users and suppliers, be increased in the near future. Various and diverse comments were received on how this might be accomplished. All suggestions, including those received from the post-Workshop questionnaire are to be considered.

ACKNOWLEDGEMENT

Sincere gratitude is extended to all at AMMRC who helped in planning and carrying out the Workshop and in preparing this record of the proceedings. Particular thanks go to R. Gagne for the many and varied tasks he carred out; to F. Quigley, Chief of the Process Development Division and technical monitor of the DARPA project; E. Kula, Chief of the Metals Research Division, and F. R. Larson, Chief of the Materials Development Laboratory for their support and encouragement and finally to the Planning Directorate for direct financial support of the Workshop and these proceedings.

RESULTS OF THE POST-WORKSHOP QUESTIONNAIRE

R. D. FRENCH and F. HODI
ARMY MATERIALS AND MECHANICS RESEARCH CENTER

Shortly after the Workshop, a questionnaire was mailed to the attendees in order to obtain their impressions of the subject matter and of the Workshop itself. The questions were directed at industry since one reason for the Workshop was to seek industrial guidance for Government sponsored research. Comments were also solicited and received from non-industrial attendees, but the response to the questionnaires is primarily the opinion of the industrial segment of the Workshop audience. More than eighty-two percent of the questionnaires were returned with information on industrial interest and many new suggestions for the next steps to be taken in the further development of Rheocasting and related secondary processes.

Not all of the questions were answered on individual returns. Furthermore, some questions permitted multiple replies. Therefore, the data reported here are presented as a percentage of the number of responses to a particular question.

Since those companies, agencies, and laboratories who received invitations to the Workshop were free to send someone from any part of their organizations, it was important to first obtain a description of the actual audience. Most of those companies, it turned out, were of moderate to large size with only thirteen percent reporting employment of less than one hundred persons. Figure 1 shows that the single largest group of companies represented was that of the producers of finished hardware and products. The next largest was the producers of finished shapes. At the other end of the scale, primary metal and alloy producers accounted for nine percent of the audience. Company representatives were largely from R&D and Engineering although Production, Marketing, and Executive Staffs were also present (Figure 2). This is not surprising since Rheocasting is only about six years old and can be described as being in an early stage of development where the first signs of profitable commercial applications are beginning to appear.

Also, since Rheocasting and related processes are in a rather early stage of development, the moderately small level of current company involvement,

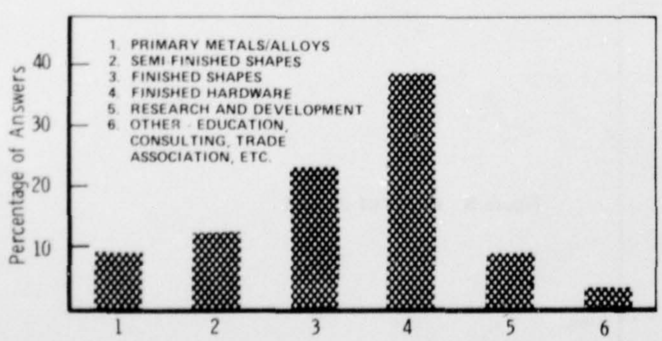


Figure 1. Business

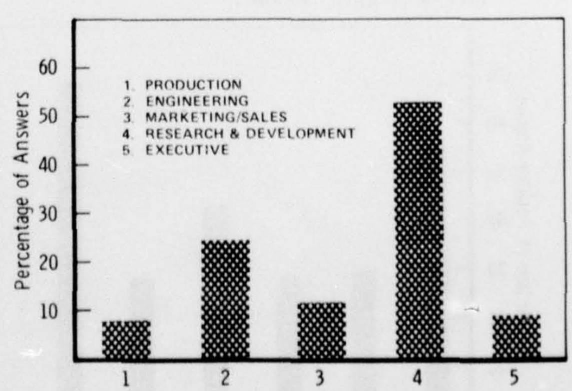


Figure 2. Branch of organization

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indicated in Figure 3, is not surprising either. It is important to note, however, that the potential for industrial involvement is reported to be much larger than current involvement in every case and that, according to Figure 4, users of the material represented the largest single group responding to the question. In other words, applications oriented people are seeing potential uses for the material that might cause them to become involved with one or more of the new processes. It is also interesting to note that this Workshop audience saw the greatest potential in Thixoforging with Compocasting, Thixocasting, and Rheocasting following in that order.

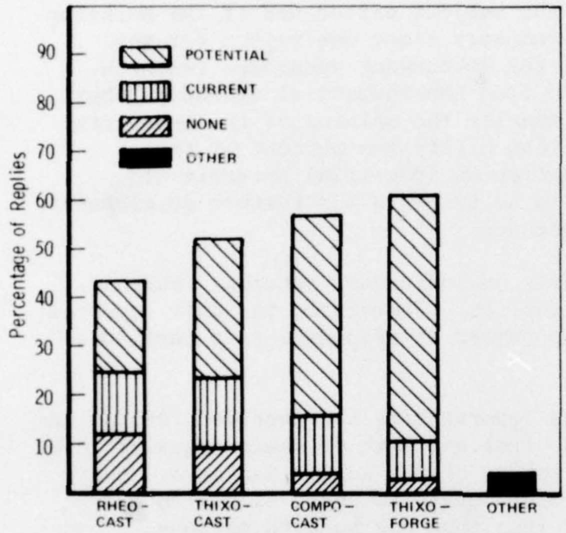

Figure 3. Interest in rheocasting - company involvement

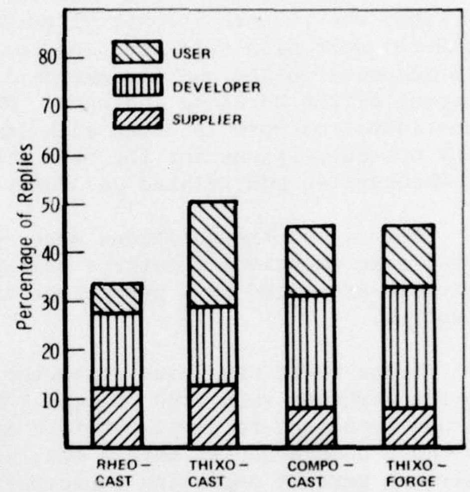

Figure 4. Interest in rheocasting - company role

Alloys of interest are noted in Figure 5. Steel and aluminum alloys receive most of the attention. The relatively high level of interest in nickel alloys probably reflects the number of attendees associated with turbine engine hardware.

More than 86% of those responding stated that structural properties were a major interest. However, more than 83% also stated that economics represented their principal interest. For the most part, therefore, economy precedes mechanical properties in the order of interest. This does not mean that cost cannot be traded off against mechanical properties, only that cost has a higher value.

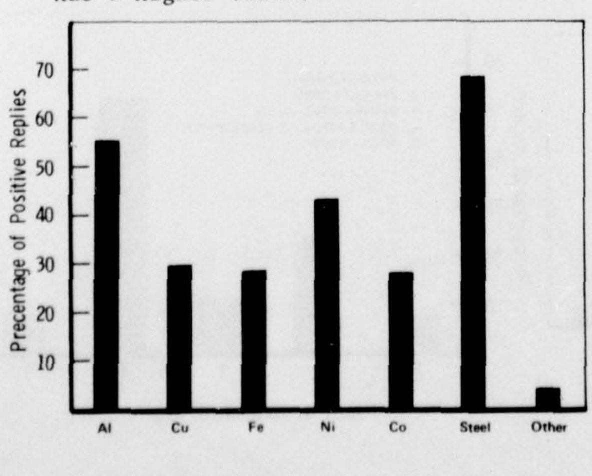

Figure 5. Alloys of interest

Throughout the Workshop presentations, an issue on the breadth and depth of available mechanical property data was continually raised. Yet it was clear from the questions asked that the attendees had in mind a broad spectrum of applications with an equally broad spectrum of requirements for mechanical properties and other physical characteristics. Just how broad can be seen in Figure 6. When combined with the alloys of interest shown in Figure 5, the number of opportunities for a continuing development program becomes quite large.

Seventy percent of the respondents answered the question on availability of material with seventy-two percent of these indicating that the sources of Rheocast, Thixocast, Compocast, and Thixoforged materials are insufficient. Their projected use of single batches from 20 to 1,000 pounds are thought to represent R&D interests. On a continual basis, the range of interest is from 100 pounds per year to more than 3,000 pounds per day. At the low end this might still represent an R&D interest, but the high end is almost certainly a production estimate.

Most respondents (97%) found the Workshop helpful with somewhat less satisfaction with the breadth of coverage (89%) and depth of coverage (70%). Ninety-five percent said they would attend another Workshop on the subject with the majority (61%) preferring a one year separation; the rest preferred two years. Additional comments on suggested next steps for the Government sponsored R&D program are too numerous to list separately. However, all but one of the respondents had something to say on this point with the strongest interests being in mechanical properties (32%), economic analyses (14%), and the availability of materials (14%). The extra interest given to these subjects which had been covered by other specific parts of the questionnaire is considered important.

The Army Materials and Mechanics Research Center is most grateful to those who responded to the questionnaire and to others who were unable to attend the Workshop, but who took the time to forward their comments on the subject. This response from industry is being used in giving direction to the continuing development program. The possibility of another Workshop on the same subject at a later time is being considered.

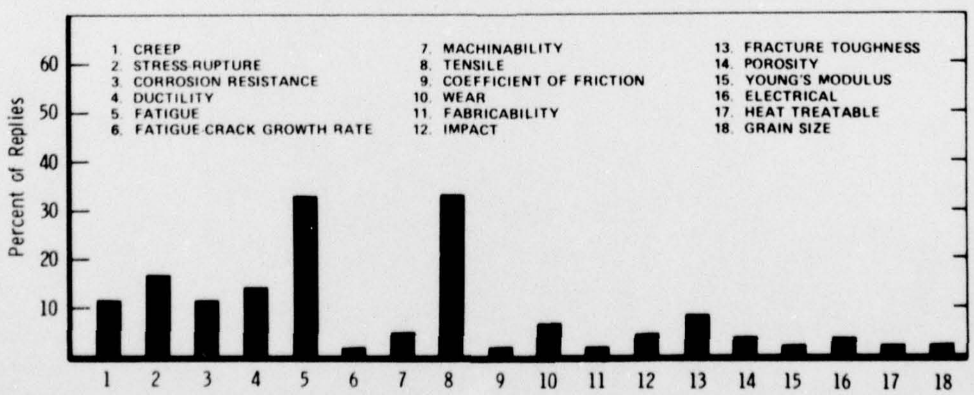

Figure 6. Properties and physical characteristics critical for applications in mind